



HELSINKI UNIVERSITY OF TECHNOLOGY
FACULTY OF INFORMATION AND NATURAL SCIENCES
DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING

Using Delaunay Triangulation in Infrastructure Design Software

Master's Thesis

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TEKNILLINEN KORKEAKOULU
INFORMAATIO- JA LUONNONTIETEIDEN TIEDEKUNTA
TIETOTEKNIKAN LAITOS

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| <p>Infrastruktuurin suunnitteluohjelmistoissa, kuten tien-, rautatien-, sillan-, tunnelin-, ja ympäristösuunnitteluohjelmistoissa, on Suomessa perinteisesti käytetty maaston pinnan mallintamiseen mittapisteistä muodostettua epäsäännöllistä kolmioverkkoa. Muualla maailmassa ovat käytössä olleet säännölliset neliö- ja kolmioverkot, maaston approksimointi ilman pintaesitystä, sekä joissain tapauksissa algebralliset pintaesitykset.</p> <p>Pinnan approksimaatiota tarvitaan em. sovelluksissa mm. pisteen korkeuden arviointiin, 2-ulotteisten murtoviivojen interpolointiin maaston pinnalle, korkeuskäyrien laskemiseen ja massan (tilavuuden) laskentaan annetuilta alueilta sekä visualisointiin.</p> <p>Delaunay-kolmiointi on tapa muodosta 2-ulotteisesta pistejoukosta epäsäännöllinen kolmioverkko, jonka kolmiot hyvin tasamuotoisia. Kolmioiden tasamuotoisuus on oleellisesta pintamallin tarkkuudelle.</p> <p>Tässä työssä tutkitaan Delaunay-kolmioinnin käytettävyyttä maaston mallintamiseen suurilla pistejoukoilla, sekä epäsäännöllisen kolmioinnin käytettävyyttä em. tehtäviin. Työssä vertaillaan Delaunay-kolmioinnin muodostamisen ajan ja muistin kulutusta pintaesityksen muodostamiseen muilla menetelmillä. Lisäksi tutkitaan näin muodostettujen pintamallien tilavuuslaskennan ja interpolaation nopeutta ja tarkkuutta.</p> | | | |
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Abstract of Master's Thesis

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In Finland, irregular triangulation has traditionally been used in infrastructural design software, such as road, railroad, bridge, tunnel and environmental design software, to model ground surfaces. Elsewhere, methods like regular square and triangle network, approximating surface without a surface presentation, and algebraic surfaces, have been used for the same task.

Approximating the ground surface is necessary for tasks such as determining the height of a point on the ground, interpolating 2D polylines onto the ground, calculating height lines, calculating volumes and visualization.

In most of these cases, a continuous surface representation, a *digital terrain model* is needed. Delaunay triangulation is a way of forming an irregular triangulation out of a 2D point set, in such a way that the triangles are well-formed. Well-formed triangles are essential for the accuracy of the surface representation.

This Master's Thesis studies how much time and memory it takes to form a Delaunay triangulation for large point sets, and how Delaunay triangulation compares to other methods of forming a surface representation. In addition, the run-time and accuracy of the resulting surface representations is studied in different interpolation and volume calculation tasks.

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Table of Contents

| | |
|---------------------------------------------------------------------------|----|
| Table of Contents | iv |
| Terminology and Abbreviations | vi |
| List of Figures | ix |
| List of Diagrams | x |
| List of Tables..... | x |
| 0 Foreword | xi |
| 1 Introduction | 1 |
| 2 Problem Statement..... | 4 |
| 2.1 Scope of Thesis | 4 |
| 2.2 Triangulation of an Irregular Point Set..... | 5 |
| 2.2.1 Arbitrary Triangulation | 7 |
| 2.2.2 Quality of the Triangulation..... | 8 |
| 2.2.3 Delaunay Triangulation..... | 9 |
| 2.2.4 Other Criteria | 11 |
| 2.3 Alternative Approaches..... | 13 |
| 2.3.1 Regular Grid (Rectangular) Triangulation..... | 13 |
| 2.3.2 Bézier surfaces and Non-uniform B-Spline surfaces | 14 |
| 2.3.3 Direct Point Interpolation..... | 15 |
| 3 Infrastructure Design Software and Workflow | 18 |
| 3.1 Input Data Considerations for the Infrastructure Design Process | 20 |
| 3.2 Quality of the Input Data | 21 |
| 4 Triangulation Algorithms..... | 22 |
| 4.1 Algorithms Categories | 22 |
| 4.1.1 Sweepline Algorithm | 22 |
| 4.1.2 Divide-and-conquer Algorithm | 23 |
| 4.1.3 Radial Sweep Algorithm | 25 |
| 4.1.4 Step-by-step Algorithm..... | 27 |
| 4.1.5 Incremental Algorithm..... | 28 |
| 4.1.6 Convex Hull Based Algorithms..... | 31 |
| 4.1.7 Specialized Cases..... | 32 |
| 4.2 Point Data Triangulation with Fold-lines..... | 32 |
| 4.2.1 Other Approaches | 34 |
| 4.2.2 Additional Constraints | 34 |

| | | |
|-------|----------------------------------------------------------|----|
| 5 | Manipulating and Using an Existing Triangulation | 35 |
| 5.1 | Adding a Point..... | 35 |
| 5.2 | Adding a Set of Points..... | 36 |
| 5.3 | Deleting a Point..... | 36 |
| 5.4 | Deleting a Set of Points..... | 37 |
| 5.5 | Folding with a Line or a Polyline..... | 37 |
| 5.6 | Simplifying the Triangulation..... | 38 |
| 5.7 | Artificially Refining the Triangulation | 39 |
| 5.8 | Interpolating a Height Value for a 2D Point..... | 41 |
| 5.9 | Interpolating a Line or a Polyline | 43 |
| 5.10 | Calculating Volume..... | 44 |
| 6 | Implementation Considerations..... | 45 |
| 6.1 | Robustness of the Triangulation Algorithm | 45 |
| 6.2 | Data Structures | 47 |
| 6.3 | Multi-threading | 48 |
| 6.4 | Non-General Purpose Processors..... | 49 |
| 7 | The Implementation and Evaluation | 50 |
| 7.1 | The Implementation | 50 |
| 7.1.1 | Data Structures..... | 50 |
| 7.1.2 | Triangulation Algorithm | 53 |
| 7.1.3 | Complexity Analysis | 54 |
| 7.1.4 | Interpolation Algorithms..... | 55 |
| 7.1.5 | Volume Calculation Algorithm..... | 55 |
| 7.2 | Environment..... | 56 |
| 7.3 | Evaluation of the Implementation against Other DTMs..... | 58 |
| 7.3.1 | Sample Data..... | 58 |
| 7.3.2 | Other Digital Terrain Models | 62 |
| 7.3.3 | Run-time..... | 63 |
| 7.3.4 | Accuracy in Interpolation of a Point | 66 |
| 7.3.5 | Accuracy in Interpolation of a Polyline..... | 68 |
| 7.3.6 | Accuracy in Volume Calculation | 69 |
| 7.3.7 | Previous Work..... | 72 |
| 8 | Conclusion..... | 73 |
| | References..... | 75 |

Terminology and Abbreviations

| | |
|--------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2D | Two-dimensional (usually x and y coordinates) |
| 3D | Three-dimensional |
| CAD | Computer-aided Design |
| Delaunay criterion | A triangle in a TIN fulfills the Delaunay criterion if no other points than the three triangle vertices lie inside the circle drawn via the three vertices. The circle is called the Delaunay neighborhood of the triangle. |

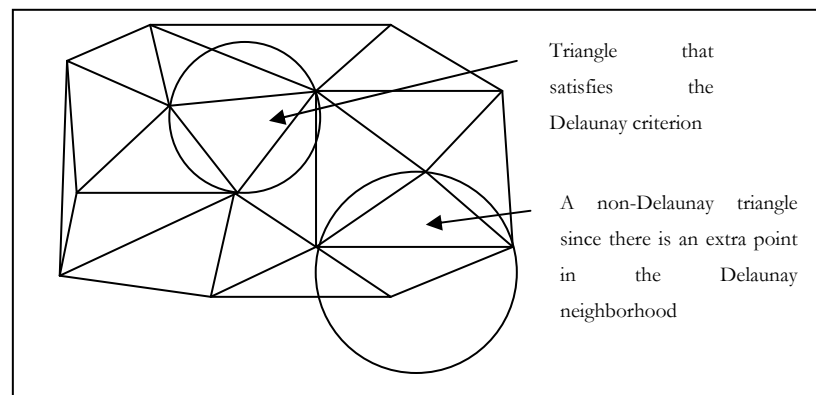


Figure: *Delaunay criterion*

| | |
|-----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Delaunay triangulation | A TIN is a <i>Delaunay triangulation</i> if and only if <u>all</u> of its triangles satisfy the Delaunay criterion. A Delaunay triangulation for a given set of points is unique, unless there are triangle-pairs where both middle-edge alternatives give two Delaunay fulfilling triangles. |
| DTM (Digital Terrain Model) | Numerical model of the measured (or planned) terrain surface. |
| Edge-neighbor | A triangle that shares an edge (and two vertices) with another triangle. |
| Edge-swap | A triangle-pair has four non-common edges, and one common edge (middle-edge). For fixed four non-common edges, the middle-edge can be chosen in two ways. Edge-swap is an operation on triangle-pair that changes the middle-edge from one alternative to the other. |
| Fold-line | A line via which the edges of a TIN are forced to go |
| GIS | Geographic Information System |
| Middle-edge | The common edge in a triangle-pair. |

Min-max criterion

Min-max criterion (minimum-maximum) says that in a triangle-pair, the middle-edge should be chosen so that the largest angle of all six angles in the triangle-pair is as small as possible.

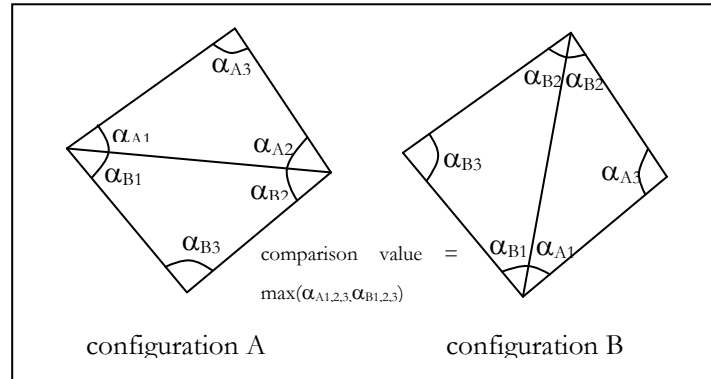


Figure: Min-max criterion

Point-neighbor

A triangle that shares one or two points with another triangle.

Quad-edge

See Triangle-pair

Tachymeter

A tachymeter or tacheometer is a kind of theodolite used for geographic measurements. It measures, optically or electronically, the distance to target. Tachymeters are often used in surveying. Having accurately measured the lengths and angles of the sides of triangles in a triangle network or chain, the shape of the ground can be calculated.

TIN (Triangular Irregular Network)

A geometric structure that consists of points (vertices), edges that connect the points and triangles. Each triangle has three edges and three points. Each edge connects two points. Each point can belong to one or more triangle and one or more edge. Each triangle has three edge neighbors, unless it is a border triangle.

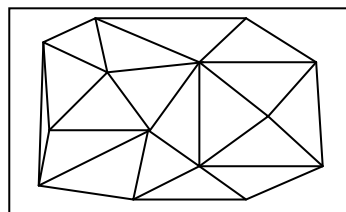


Figure: Simple TIN

Triangle-pair

Two edge-neighbor triangles (triangles with common edge). Also called a quad-edge.

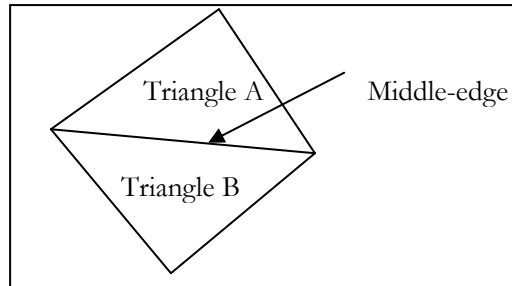


Figure: *A triangle-pair*

Voronoi diagram

Voronoi diagram divides the plane into regions whose all points are closer to the point that defines the region than to any other point of the set

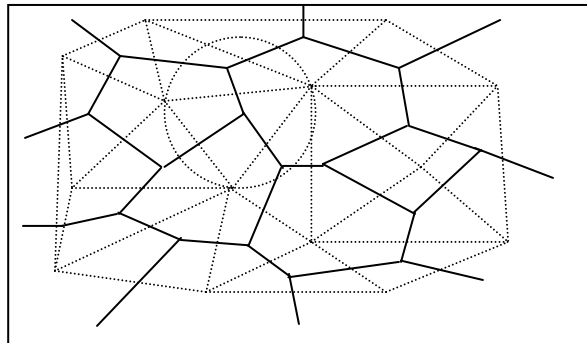


Figure: *Voronoi diagram (the corresponding Delaunay triangulation drawn with dashed line)*

List of Figures

| | | |
|------|-------------------------------------------------------------------------------------------|----|
| 1.1 | Interpolating a point from a set of measured points | 3 |
| 2.1 | An overhang where an x, y point has three different z values | 6 |
| 2.2 | Perspective view of a TIN | 7 |
| 2.3 | Intuitive triangulation retains the form of the ridge | 9 |
| 2.4 | A different triangulation would obviously produce dubious results for point interpolation | 9 |
| 2.5 | A Delaunay triangulation with one non-Delaunay triangle pair | 10 |
| 2.6 | A Voronoi diagram | 11 |
| 2.7 | A T-junction | 12 |
| 2.8 | A regular triangulation from the same data as in Figure 2.2 | 13 |
| 2.9 | Interpreting point data as matrix | 14 |
| 2.10 | Regular triangulation | 14 |
| 4.1 | Divide-and-conquer algorithm: Merge step | 24 |
| 4.2 | Radial sweep algorithm: Initial edges sorted by their angles | 26 |
| 4.3 | Radial sweep algorithm: Triangles formed between the edges | 26 |
| 4.4 | Radial sweep algorithm: Non-convex notches filled | 26 |
| 4.5 | Radial sweep algorithm: Triangulation is refined to satisfy Delaunay-criterion | 26 |
| 4.6 | Step-by-step algorithm: Initial base line is chosen and the first apex is sought | 28 |
| 4.7 | Step-by-step algorithm: New edges are appended to edges-to-do stack | 28 |
| 4.8 | Incremental algorithm: An initial triangulation is formed | 30 |
| 4.9 | Incremental algorithm: Points are inserted to the triangulation one by one | 30 |
| 4.10 | Incremental algorithm: While inserting the points, the Delaunay criterion is maintained | 30 |
| 4.11 | Incremental algorithm: After inserting all the points, we have a Delaunay triangulation | 30 |
| 4.12 | Incremental algorithm: The triangulation is made convex again | 31 |
| 7.1 | The reference surface | 58 |
| 7.2 | Sample point set for N=5000 | 60 |
| 7.3 | The Delaunay triangulation of sample point set from Figure 7.2 | 61 |
| 7.4 | The real world data set from Vuotos area | 62 |
| 7.5 | Comparing regular grid triangulation to the Delaunay triangulation of the point set | 63 |
| 7.6 | Comparing the intersections from Delaunay triangulation and regular grid triangulation | 69 |
| 7.7 | The sample Delaunay triangulation from Figure 7.3 compared to $z=0$ | 70 |

List of Diagrams

| | | |
|-----|-----------------------------------------------------------|----|
| 7.1 | The run-time of the two methods | 64 |
| 7.2 | The point interpolation error of the two methods | 66 |
| 7.3 | Comparing the interpolation accuracy with real world data | 68 |

List of Tables

| | | |
|-----|--------------------------------------------------------------|----|
| 7.1 | The run-time of interpolation and volume calculation | 65 |
| 7.2 | The volume calculation results of the two methods | 71 |
| 7.3 | The volume difference calculation results of the two methods | 72 |

0 Foreword

This Master's Thesis has been made in the end of year 2008 and beginning of 2009 in Vianova Systems Finland Oy. I would like to thank development manager Timo Ruoho for allowing me to work on this thesis at Vianova.

Vianova Systems Finland is an inspiring place to work, but what was miraculous was that there was also serene enough atmosphere to concentrate on such a long-term work. This wouldn't have been possible without Vianova's help in arranging the projects so that there was a long quiet period to work on the thesis. I also wish to thank all my colleagues and Vianova Systems Finland.

Delaunay triangulation, its mathematical background and its good characteristics in the practical applications are an interesting subject. The whole area of computational geometry is somewhat underrepresented in the current computer science education. I hope in future more people will find this area interesting.

Espoo January 12th 2009

Ville Herva

1 Introduction

Before design projects such as road, railroad, building and environment designs can be started, the affected area needs to be surveyed. This process involves measuring the locations of existing buildings, delves and other stationary objects. Most importantly, the shape, consistency and composition of the surface must be surveyed. Consistency and composition is usually measured by drilling samples off the soil. The volumetric distribution of different soil types is then interpolated between the sample drill points [PP98].

The shape of the surface is measured with methods such as tachymeters, GPS and aerial photographs (see section 3.1). The data these methods yield is arbitrary point data – a large number of points on the surface whose X , Y and Z coordinates are known accurately. Often, it is assumed that the surface is 2.5-dimensional – that is, for a given 2-dimensional location (x, y) there is only one point (x, y, z) that lies on the surface. Depending on the method used, the number of sample points on a given area can vary wildly. Also, the accuracy and type of error of sample points varies [Nur02].

Because the survey raw survey data only consists of a set of points that lie on the surface, a method of constructing an approximation of the actual surface is needed. Without a representation of the surface, such tasks as calculating Z of given (x, y) or calculating height line for given Z , cannot be carried out. It is clear that we need a continuous representation of the surface that is defined for every point (x, y) on the area.

In infrastructure design, this representation is usually referred to as *Digital Terrain Model (DTM)*. First digital terrain models date back to 1958 (due to Massachusetts Institute of Technology professor Charles Miller), but they became popular in commercial infrastructure design in the 1980's. Closely related term to DTM is *Digital Elevation Model (DEM)*. In digital elevation model, there is a height value for each two-dimensional point either in the form of a height matrix or a raster file or a there is a mean to calculate the height from the DEM [HD06].

Before we can decide what kind of a representation we should choose, we will have to know the operations we will use the representation for. For a typical civil engineering project, these operations include

- Interpolating heights for arbitrary points on the area
- Solving the 2D-polyline that is the intersection of the surface representation and a XY -plane on a given height (the height line)
- Computing the volume between the volume between the surface representation and a XY -plane on a given height on a given XY -area
- Computing the volume between the volume between the surface representation and the representation of another surface on a given XY -area
- Computing the intersection of between the surface representation and objects such as 3D-line, 3D-plane or another surface representation
- Visualization: polygon rendering, ray-tracing etc.

These are the most common applications [HHKL09]. In specialized tasks, digital terrain models are used for calculation the flow of water, estimating the visibility, calculating noise propagation and so on. These uses of DTM pose their own requirements for the surface representation, but they are outside of the scope of this thesis.

Although we only *know* the height of the terrain where we have measured it, not anywhere else, interpolating a height for a point can be easily accomplished for almost any kind of surface representation. However, additional requirements are often posed for this operation. For example, it is often required that when interpolating the height for a point from the representation in a measured point, the result must be the measured height. This makes a lot of sense, since the measured points are the only ones we *know* the height at. However, this excludes some popular variations of curved surfaces, such as Bézier surfaces. Other requirement might be that when interpolating points on a 2D-path, there may not be discontinuations (that is, when the 2D-distance of two sample points approaches zero, the height difference does not approach zero). If the surface representation satisfies this criterion, it is said to be (first order) continuous. Sometimes even second order continuousness (the derivative of the surface is continuous) is desired. In most cases, the height can be accurately solved – that is, a direct algebraic solution exists [BKOS97].

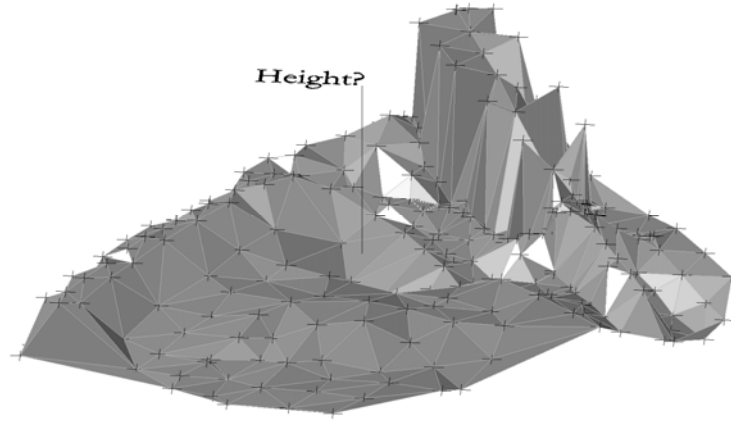


Figure 1.1: *Interpolating a point from a set of measured points (shown with crosses).*

In infrastructure design software, the soil surface has traditionally been represented with either triangle irregular network (TIN) or a regular square network. In Finland, TIN has been more popular, and in other Nordic Countries, square network has been used more [HHKL09].

There are several quality criteria for TINs. One of the most widely accepted is so-called Delaunay criterion. A TIN that satisfies the Delaunay criterion will have well formed triangles, whose edges are not too long and angles too narrow [HD06]. Delaunay triangulation has been used in some infrastructure design software packages.

2 Problem Statement

2.1 Scope of Thesis

In this thesis, I intend to study the algorithms for creating, updating and using Delaunay triangulation in infrastructure design applications. I will compare Delaunay triangulation to other alternatives based on the following criteria:

- accuracy
- robustness (whether the method is prone to special cases where the results are unpredictable)
- runtime
- memory use
- simplicity of implementation

For infrastructure design application, the following operations are crucial:

- creating the surface representation
- updating the surface representation (deleting and adding points)
- interpolating heights of 2D points and polylines
- calculating volumes.

To evaluate how suitable Delaunay triangulation is for infrastructure design application, I will implement these operations for Delaunay triangulation and chosen alternative surface representations. Based on their popularity in current infrastructure design software packages, I have chosen regular grid triangle network and direct interpolation from the point data as the competing surface representations.

I will compare the accuracy and run-time with both ideal sample data (whose accurate form is known) and real-world data. Because real-world data is measured only at sample sites, the true formation of the surface is represented is not known. This makes it somewhat harder to draw reliable conclusions of the accuracy of the methods. However, with certain procedures which I will present later, some conclusions can be drawn.

I will also discuss algorithms to implement Delaunay triangulation from point data and point data with fold-lines. I will describe in more detail the algorithm I chose to implement and comment its run-time and memory use compared to others.

2.2 Triangulation of an Irregular Point Set

A planar map is a topological map on a 2D plane. It divides the plane into faces that consist of edges that define their boundary. Thus, a face is a polygon. The edges are line segments that begin from the origin vertex and end at destination vertex (although the direction of the edge is not important for all applications.) For a planar map to be complete, each edge should be neighbored by two faces, unless it is a boundary edge for the whole planar map. Each vertex must be connected to one or more edges and no edges may cross.

Forming a planar map of a surface described by a given point set is a common way to represent the surface in continuous manner. When forming the planar map, we consider the point set as 2D – that is, the z coordinate does not affect the shape of the planar graph – but we maintain the z coordinate as an attribute that can later be used for the interpolation and volume calculation operations.

We can form a planar map using however complex polygons as faces as we please. If one looks at the world map, one can consider the countries (and the sea) as very complex polygons, and the map is thus a planar map (ignoring the spherical projection). However, when modeling the terrain surface, the points carry the height information as well, and the planar map is actually not planar. In order for the interpolation and volume calculation operations to have well-defined results, the polygons need to be planar. For polygons with four or more three-dimensional vertices this is a special case, but for a triangle, this constraint is always met. On the other hand, any polygon with more than three vertices can always be divided into triangles. This is why it is common to use triangles only as the faces of the planar map.

A planar map with triangles as faces and 3D vertices is called a triangulation or a TIN (triangle irregular network.) A triangulation is a *maximal planar subdivision* of a point set, because no edges can be added to it so that it would still be a planar map.

A triangulation can be formed out of any 2D point set given that is not degenerated - that is, not all points are identical nor collinear. In practical applications, all identical points are discarded, and if any points have the same x, y but not z it is considered an error in the input data. The point set is said to be 2.5D: for any given x, y there can be only one z , and no overhangs can appear (see Figure 2.1).

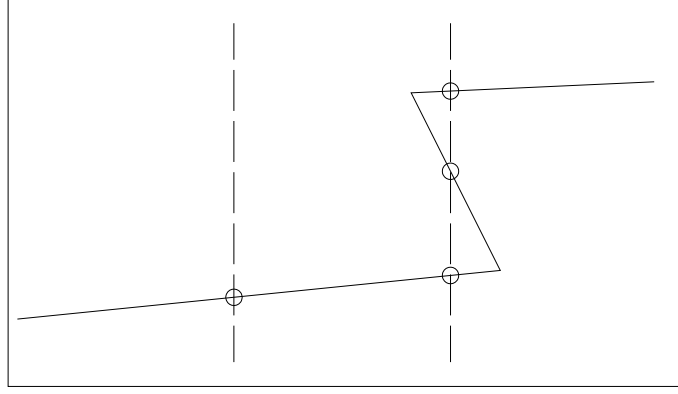


Figure 2.1: An overhang where an x, y point has three different z values.

In planar map, a face that only has boundary edges is called an *unbounded face*. Likewise, a combination of faces that form an area, whose boundaries compose of boundary edges, is called an unbounded face. For a complete planar map the only unbounded face is the union of all faces, and its boundary edges form the convex hull of the point set. A face whose all edges are non-boundary edges is a *bounded face*. Such face is surrounded by other face from all sides.

The process of forming a TIN out of a point set is called *triangulating* it, and the result is called a *triangulation*. There are several possible triangulations for a given point set (given that it has more than 3 points.) However, all these triangulations have the same amount of vertices, edges and triangles. The count of triangles can be derived from the Euler's formula. Take a point set p with n points. Its convex hull is unambiguous. Let us denote the number of points in p that lie on the convex hull with k . Any triangulation of p then has $2n - 2 - k$ triangles and $3n - 3 - k$ edges [BKOS97]. Note that the convex hull can be expressed with fewer vertexes than k if some of the points that lie on the convex hull are collinear. For these formulae, k needs to include the collinear points as well.

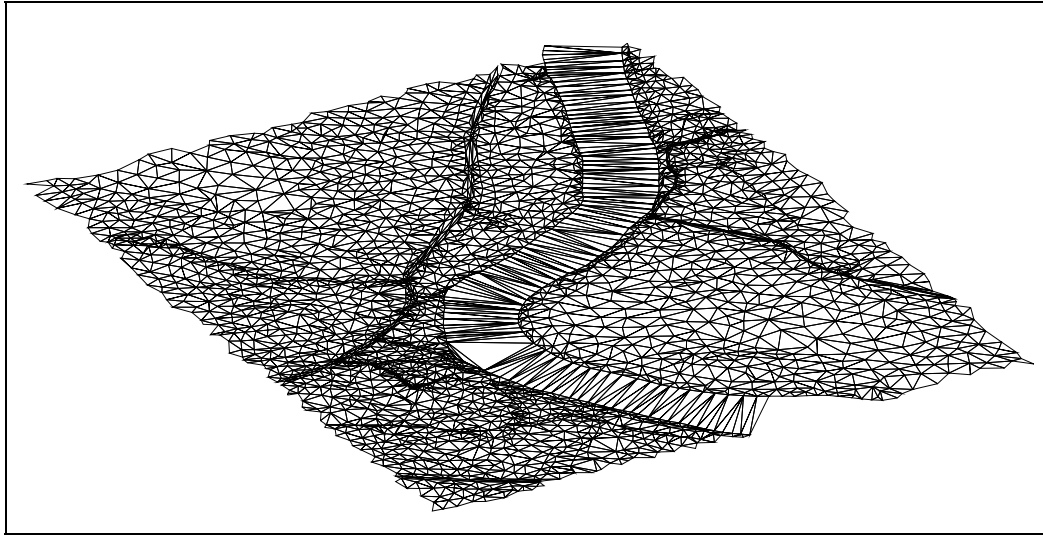


Figure 2.2: Perspective view of a TIN

2.2.1 Arbitrary Triangulation

A two-dimensional set of points can be triangulated in a number of ways. The edges of the triangles cannot be selected quite arbitrarily, because the edges of the other triangles in the triangulation may not cross them, and no vertex can be inside a triangle. This limits the number of possible triangulations of a two-dimensional point set somewhat, but it grows fast with the number of points in the set. I haven't found an estimate of the number of possible triangulations for a two-dimensional point set in the literature.

One trivial algorithm to triangulate a point set is to take its convex hull polygon, and triangulate it. Whenever there is a point inside the new triangle (or on its edge), the triangle is divided in three (or two). This subdivision is carried on recursively until there are no points inside the triangles. For example [BKOS97] discusses calculating the convex hull of a point set. There are a number of algorithms to triangulate a polygon, see for example [NM95]. Since the convex hull is convex by definition, the simplest algorithm known as ear-clipping [Eber02] can be used. In this algorithm we begin from a vertex V_i on the polygon, form a triangle of it and the two next vertices V_{i+1} and V_{i+2} . We take the vertex V_{i+1} away from the polygon and save the triangle. The vertex that was V_{i+2} before removing this “ear” is now V_{i+1} . We remove the ear V_i, V_{i+1}, V_{i+2} again and carry on until there are less than three vertices in the polygon. [For non-convex polygons, the algorithm is more complex – we must find a convex ear each time before removing it, since not all ears V_i, V_{i+1}, V_{i+2} are convex.] It is easy to see that triangulating the convex hull this way gives a fan-like triangulation that consists of long, narrow triangles. Even after proceeding with the subdivision phase described above, the triangle formation will be very uneven.

2.2.2 Quality of the Triangulation

The quality of the triangulation is defined by how well it approximates the real surface – i.e. how well heights interpolated from it correspond to the real height, and how well volumes calculated from it correspond to the real volumes. Consider the two TINs in Figures 2.3 and 2.4. They model a real ground surface that has a ridge. Both are triangulated from measured sample points. The difference between the two triangulations is the two triangles between the four vertices in marked by vertical line in Figure 2.4. Those four points can be triangulated in two ways: like in Figure 2.3 or like in Figure 2.4. In theory, the real ground surface could resemble either of the two, but it is much more likely to resemble the one in Figure 2.3. The question is: how do we make sure the triangulation we have is most likely to resemble the surface it approximates.

It turns out that a triangulation most likely to resemble the approximated surface has as short triangle sides as possible. This minimizes the distance to the vertices from any given point on the triangle. Because the vertices are the known heights of the real surface, and the real surface is likely to have similar height near the measured points, the points used for interpolation (the triangle vertices) should be selected near the interpolated point.

One alternative for finding an optimal triangulation is to minimize the sum of the lengths of the edges in the triangulation. A triangulation that has the lowest possible sum of the lengths of the edges is called the *minimum weight triangulation* (MWT) of a point set. The sum of lengths of the edges of a triangulation is called the *weight* of a triangulation.

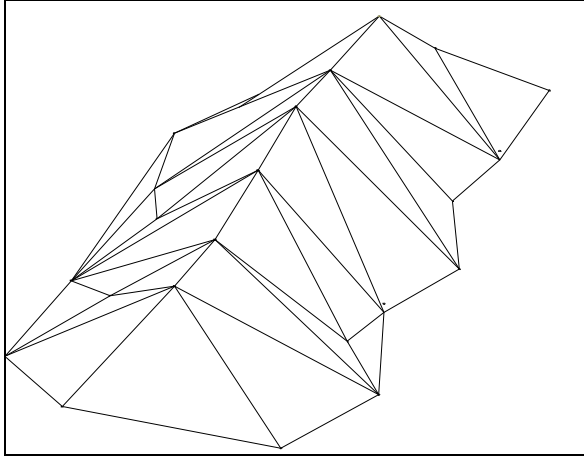


Figure 2.3: *Intuitive triangulation retains the form of the ridge.*

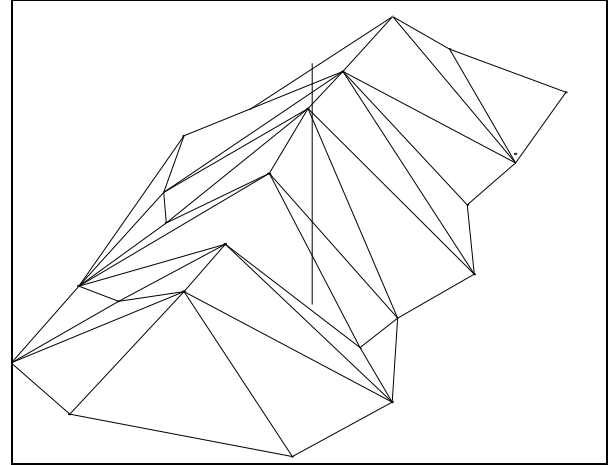


Figure 2.4: *A different triangulation (flipped edge marked with a vertical line) would obviously produce dubious results for point interpolation.*

Dickerson, McElfresh and Montague [DEM95] discuss algorithms for finding the minimum weight triangulation. They conclude that while a minimum weight triangulation can be computed for some polygons in $O(n^3)$ time, finding a minimum weight triangulation for an arbitrary point set is substantially harder. Mulzer and Rote recently proved that finding MWT is NP-hard [MR08]. They therefore focus on finding good approximations of minimum weight triangulation. Delaunay triangulation discussed in the next section is one such approximation.

A notable difference between a Delaunay triangulation and minimum weight triangulation is that while local optimization (through edge-flips with min-max criterion) eventually yields a global Delaunay triangulation, local optimization will not yield a minimum weight triangulation. In fact, [DEM95] defines a term *local minimality* that means that the triangulation cannot be locally optimized any further; in other words, there exists no edge-flip that would yield a triangulation with better weight. Such triangulation is called *locally minimal triangulation*.

2.2.3 Delaunay Triangulation

Introduced by Boris Delaunay in 1934, the *Delaunay triangulation* is a planar subdivision that divides a point set on a plane into such triangles that no other point is inside the circle defined by the three vertices of the

triangle. Delaunay triangulation minimizes the angles of the triangles. This avoids long and narrow triangles.

The *Delaunay criterion* states that the circumcircle (the circle defined by the three vertices of the triangle) of a triangle may not contain other points but the three belonging to the triangle itself. Other points are accepted on the perimeter of the circle, but not inside it. This criterion must hold for all triangles in the triangulation if the triangulation is a Delaunay triangulation [BKOS97].

It is possible to construct a Delaunay triangulation of any set of points, provided that the set is not degenerate – i.e. all the points may not lie on the same place or on the same line. If there are more than three points on the perimeter of the circumcircle of a triangle in the triangulation, the Delaunay triangulation is not unique. This is the case, for example, when triangulating the four points of a rectangle – a situation that appears often with the real world data.

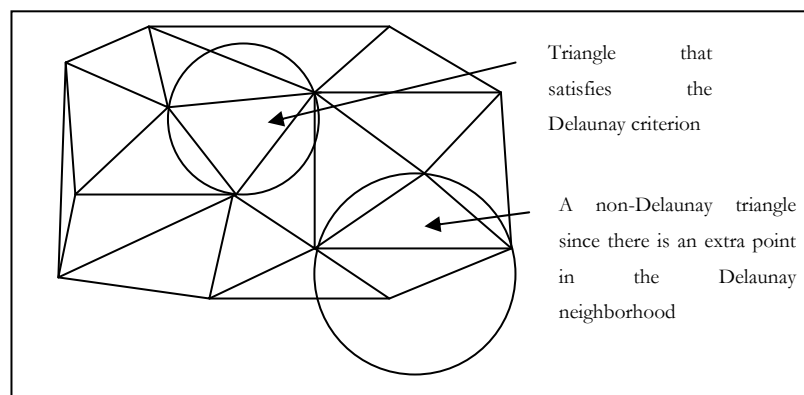


Figure 2.5: A Delaunay triangulation with one non-Delaunay triangle pair.

The Delaunay triangulation maximized the minimum angle of the triangles. Thus, it is guaranteed, that the minimum angle of the triangles of the Delaunay Triangulation is not smaller than that of any other triangulation of the same point set.

The boundaries of the Delaunay triangulation also define the convex hull of the points set because the Delaunay triangulation is a maximal planar subdivision. This is a useful characteristic of Delaunay triangulation, but in practice, the triangulation will often need to be bounded so that there are concavities on areas that are not of interest or where there is not input data available.

The original definition applied for a point set in two dimensions. It possible to generalize the Delaunay triangulation to more dimension; for example the equivalent for three dimensional space is called the *Delaunay tetrahedralization* where no other point may be inside the sphere defined by a tetrahedron.

Finding the two dimensional Delaunay triangulation of a set of point is equivalent of projecting the set on a 3D paraboloid ($z = x^2 + y^2$) and finding the convex hull of that point set. This concept can also be generalized to more dimensions.

The Delaunay triangulation is the dual of the *Voronoi diagram* invented by Georgy Voronoi in 1908. Given a plane and a set of points, the Voronoi diagram divides the plane into regions whose all points are closer to the point that defines the region than to any other point of the set. The edges of the diagram are equidistant from two points, and the nodes of the diagram are equidistant from three or more points. Finding the Voronoi diagram for a set of points is equivalent of finding the Delaunay triangulation for it.

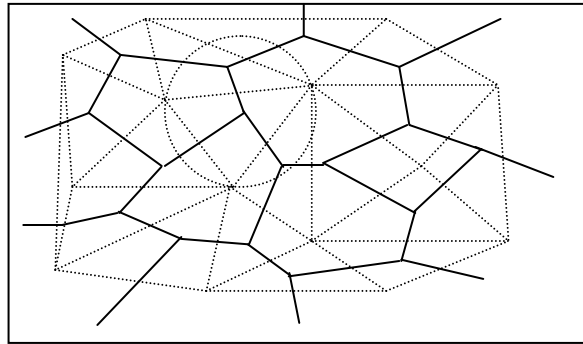


Figure 2.6: *A Voronoi diagram.*

2.2.4 Other Criteria

In infrastructure design applications, there are a few other criteria for a good triangulation. For example, height lines are often generated from the DTM. Height lines are often used in maps to visualize the elevations of the ground. Calculating a height line for a given height means intersecting the DTM with a horizontal plane at that height. But what if there was a planar triangle at that height? The result would then be undefined. For this reason, planar triangles whose vertex heights are all same are often avoided in DTMs.

In visualization applications, so called *T-junctions* are avoided. In T-junctions, there is a vertex on an edge of another triangle (see Figure 2.7.) These T-junctions cause visualization artifacts because of the way the graphics hardware depth buffering works. In a Delaunay triangulation, there can be no T-junctions, but this problem can arise if the triangulation is processed e.g. reduced for visualization without care.

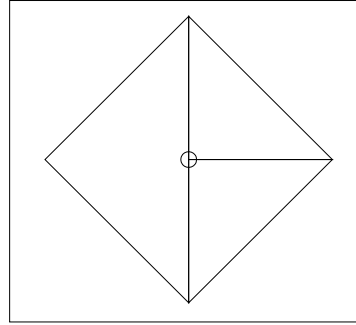


Figure 2.7: *A T-junction.*

2.3 Alternative Approaches

2.3.1 Regular Grid (Rectangular) Triangulation

Some surveying methods give regular point distributions. For example, some methods give a regular orthogonal lattice of points. Forming a triangulation for such point set is of course trivial; take four neighboring points, and form two triangles from them (as shown in Figure 2.10). Calculating this kind of triangulation is fast; the running time is linear. The triangulation is also well-formed; it is easy to see that it satisfies the Delaunay criterion.

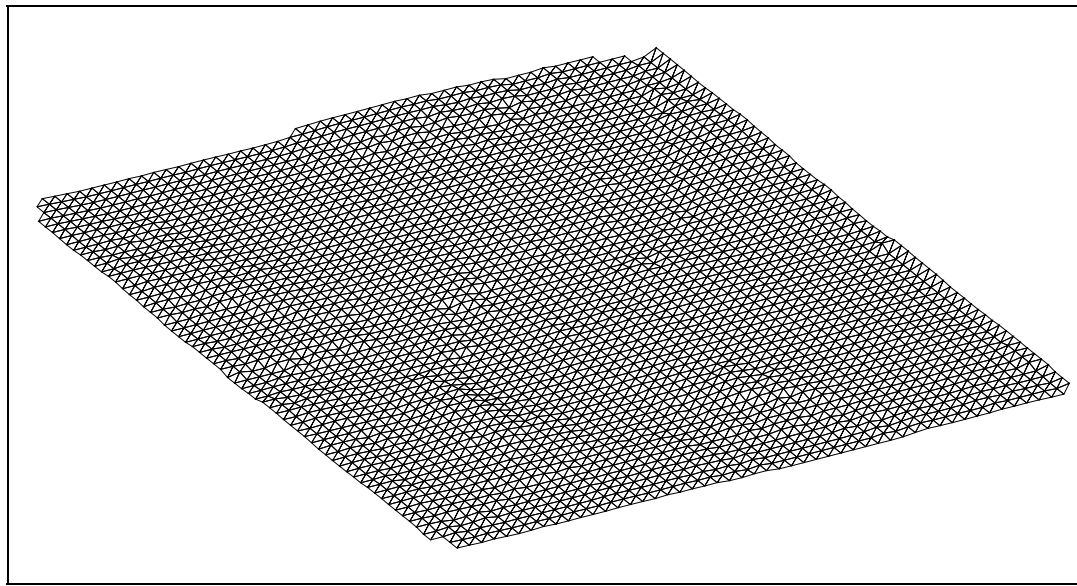


Figure 2.8: *A regular triangulation from the same data as in Figure 2.2.*

Because forming regular triangulation is fast and gives a well-formed triangulation, it is sometimes even worth interpolating a set of regularly distributed points from an irregular point set and then proceed to triangulate them. This has the advantage of being able to decide how dense the triangular network will be. On the other hand, the surface approximation will not be too accurate (depending on the chosen point interpolation method.) The resulting mesh is however well-formed and suitable for example for visualization purposes. In some cases, the original (irregular) point set is so large that this is the only feasible approach. It may also be worthwhile if accuracy is not a great concern.

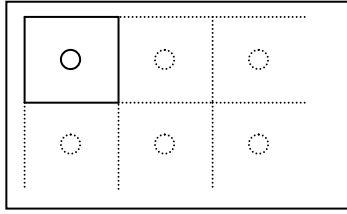


Figure 2.9: *Interpreting point data as matrix.*

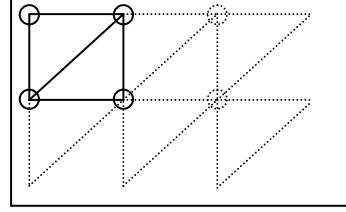


Figure 2.10: *Regular triangulation.*

Even simpler approach is to interpret the regular point set as a matrix that maps a given point (x, y) and the surrounding square (cell) to a Z . This way, interpolating Z for a sample point reduces to looking up the cell the sample point resides, and returning the associated Z . This can be done in constant time. Of course, the results are discrete, but sometimes it is worth exploiting the speed advance despite the lesser accuracy.

2.3.2 Bézier surfaces and Non-uniform B-Spline surfaces

Non-uniform B-Splines (NURBSes) polynomial surface representations, developed for computer aided design. They can represent any three-dimensional surfaces. Because the increasing complexity, complex surface are usually represented with several NURBS patches. The most commonly used NURBS surface is the Bézier surface [PT97].

Bézier surfaces were invented by French engineer Pierre Bézier who worked in automobile industry. Bézier splines have been widely used in computer graphics and computer aided graphics since 1980's. They are defined in terms of *control points*. Usually the surface does not pass through these control points, but stretches towards them. Bézier surfaces are intuitive for human design tasks such as outlining car bodies. It also makes them less suited for tasks where the surface is known before-hand and the surface representation needs to follow the measurement as closely as possible.

Bézier surface of order (n, m) is defined by equation

$$p(u, v) = \sum_{i=0}^n \sum_{j=0}^m B_i^n(u) B_j^m(v) k_{i,j}$$

which is evaluated over the unit square where

$$B_i^n(u) = \binom{n}{i} u^i (1-u)^{n-i}$$

is a Bernstein polynomial. [HLS93] This gives us the position of point \mathbf{p} as function of coordinates u and v . A Bézier surface of order (m, n) will have $n + 1$ times $m + 1$ control points.

Bézier surface can be of any order, but as we can see from the equation, the calculation burden quickly grows heavier as the order rises, and large Bézier surfaces are generally formed out of multiple simpler Bézier patches (Bézier surfaces of small order) that are fitted together.

For example Gálvez, Iglesias, Cobo, Puig-Pey and Espinola [GICPE07] describe algorithms to fit Bézier surfaces to follow 3D point sets as optimally as possible, but the algorithms for this are nowhere near as simple as for TINs and square networks.

The strong point of Bézier surfaces is their smoothness with relatively small computational overhead. This is particularly useful in computer graphics. I am unaware of any widely used infrastructure design program that uses Bézier surfaces as soil ground surface representation.

2.3.3 Direct Point Interpolation

It is not strictly necessary to have a representation of the surface to carry out certain tasks. For example, interpolating Z for a given (x, y) can be easily accomplished based solely on the point data. However, tasks such as solving height line for a given Z , or calculating the volume between two surfaces, while perhaps not impossible to accomplish without a mathematical representation of the surface, are usually done using a surface representation.

Interpolating a point from a set of points is quite straightforward and can be carried out in $O(\log N)$ time (or even faster, depending of desired accuracy). To interpolate Z for a given $p = (x, y)$ from a set of points P , the most intuitive approach is to search n nearest points (denote them with $R = p_{1...n}$) from the point data, and then calculate the average Z of $p_{1...n}$.

The n points (assuming n is constant) can be found in logarithmic time, given that the point set P is sorted or otherwise organized to a suitable data structure. Even sorting the points by X (and if X is equal, Y) and then using binary search gives logarithmic running time. More sophisticated methods such a spatial hashing [THMPG03], or quadtree [BKOS97] can give even better running time, but the performance is rarely a concern unless n is very large and a large number of points is interpolated.

The average of Z of $p_{1...n}$ can be weighted to get better accuracy. A common method is to weight the p_i in the sum with the inverse distance or inverse quadratic distance from p to p_i . The sum equation then becomes

$$z_p = \frac{\sum_i z_{p_i} \cdot \frac{1}{\text{dist}(p, p_i)}}{\sum_i \text{dist}(p, p_i)}$$

or, for quadratic distance

$$z_p = \frac{\sum_i z_{p_i} \cdot \frac{1}{\text{dist}(p, p_i)^2}}{\sum_i \text{dist}(p, p_i)^2}$$

where $\text{dist}(p_1, p_2)$ is the distance on XY -plane or

$$\text{dist}(p_1, p_2) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

Choosing suitable n is not easy. One approach is to choose a distance d , and take all the points from P whose $\text{dist}(p, p_i) < d$ rather than n nearest points. However, the density of the points can vary over the area, and just blindly choosing a d that appears sensible for most of the data could yield no points at all on certain areas. On the other hand, always taking n points farthest of which can be very far away makes no more sense. However, weighting the result with the inverse distance (or, moreover, inverse square distance) ensures that if such far-away points appear among $p_{1...n}$ their contribution to the result is negligible.

Unless the result is weighted with inverse distance, this method suffers from discontinuities. Let us assume we are interpolating a 2D line l onto the surface that the point set P approximates. We do this by sampling points from the line and interpolating their Z from P . The resulting 3D polyline is the mapping of l on the surface approximated by P . In theory, the more we interpolate points (and the smaller their distance is) the better the result is. However, just taking the average Z of $p_{1...n}$ means that two sample points that are infinitely near each other can have significant difference in their interpolated Z . This is because the points (and thus, their contribution to the result) discretely appear and disappear from the

point set included in the sum. This problem can be seen with the weighted average as well (unless $n = n_P$), but it is much smaller.

The solution would be to choose the points that are nearer than the maximum distance d , and weight their contribution so that for points whose $\text{dist}(p, p_i) \geq d$ have zero contribution and point (if any) whose $\text{dist}(p, p_i) = 0$ has infinite contribution. The contribution of points whose $d \geq \text{dist}(p, p_i) \geq 0$ could be chosen to be linear or quadratic. This way, the new points that appear in the point set begin to affect smoothly (as do the points that disappear from the set). However, it is difficult or impossible to choose the d so that the point set always contains enough points, and on the other hand never contains too many points (which ruins the running time of the algorithm.)

3 Infrastructure Design Software and Workflow

The term Infrastructure Design Software refers to Civil engineering applications that are used to design, model and maintain infrastructural objects, such as roads, railroads, bridges, tunnels, dams, airports, harbors, buildings, environment and so on. None of these are built on top of nothing, but on soil, water, rock or on other existing basis. Most of the time, the basis is soil surface. In order to design new structures or maintain or renovate old ones, the soil must be surveyed. Usually it is not enough to know the top surface of the soil, but the underlying soil layer and their materials must also be surveyed by drilling and soil radar [PP98].

The infrastructure design software suites are often built on top of more general Computer Aided Design (CAD) applications. The modern general user interface for operations like modifying geometrical primitives such as polylines has grown so complex that it doesn't make sense to reimplement that for infrastructure design software. This also allows the infrastructure design programs to utilize the visualization, import and export functionality in generic CAD packages.

The infrastructure design itself is very complex area. The design is constrained by laws, regulations, engineering guidelines and best practices that vary from country to country. Also, designing different infrastructures, like bridges or railroads, is very specialized task and requires an engineer specialized for that very task. This is why most of the current infrastructure design software suites are divided in multiple modules, one for each domain. These modules can be bought, deployed and used separately, so that a bridge specialist doesn't have to know anything about railroad design.

Engineering an infrastructure with a modern infrastructure design software package is really a computer aided design process. Instead of merely drawing the lines and arcs of the structure on the screen instead of paper, the user can take advantage of several aiding features such as calculation, simulation, visualization and constraint-based design. Again, the extent of the aids depends on the domain and software package, but it is estimated that these advantages in the design process give more than ten-fold increase in productive in some cases [HHKL09].

The process of designing, construction and maintaining an infrastructure has several phases. For example, road design process consists of pre-design, general design and construction design phases. After that, computers are used in the construction and maintenance phases. In some cases, a different software

module is used for each phase. It is said that the total time used for designing has not necessarily decreased, but the use of infrastructural design software has enabled the engineers to probe several alternatives and reach higher quality results. For example, making changes to designs imposes vastly smaller overhead, because all the drawings and scale models do not have to be redone for each change [HHKL09].

Traditionally, the end product of computer aided design process has been a paper plot (similar to that made by hand and with paper and pencil before computer aided design became popular.) The construction and maintenance phases would then use the paper plot as their guideline. The first computer aided designs were two-dimensional, mimicking the paper-and-pencil designs. Truly three-dimensional design is gaining ground surprisingly late – some of the software in use today are still two-dimensional. Fully three-dimensional designs are the trend, however.

Nowadays, the digital, three-dimensional, representation of the structure is used later and later in the process. In some cases, the actual construction machines (like diggers) use the three-dimensional digital model to create the real structure semi-automatically. Also, the maintenance phase utilizes the same digital model as basis for the maintenance database. This goal is somewhat hampered by the heterogeneity of the infrastructure data models. However, there are several intentions to harmonize the data models, such as the global LandXML standard and the Finnish Infra 2010 project [LM08].

In Finland, the most prevailing infrastructure design suites are Vianova Novapoint, Vianova VID, Tekla Xstreet, SITO Citycad, Bentley MicroStation (MXRoad, InRoads, Railtrack) and Autodesk Civil 3D [HHKL09]. Globally, the aforementioned Autodesk and Microstation products are the most popular ones, but on certain areas other software packages prevail – for example, Vianova Novapoint in the Nordic Countries and Gredo in Russia [HHKL09].

There are several infrastructure design software packages and a large number of modules, and not all of them utilize surface representations (like TINs), but most of them do. In infrastructure design, most of the structures are somehow based on or connected to ground and hence, a representation of it is required for the design.

3.1 Input Data Considerations for the Infrastructure Design Process

Infrastructures are usually designed on existing ground or on top of existing structures. There are several methods to survey the existing surface, such as GPS measurements, tachymeter surveys, laser scanning and aerial photographs. Some of the methods rely in human work to find accurate and good quality sample points. Tachymeter and GPS surveys belong to this category. In these methods, the surveyor team places the tripod on representative spots of the terrain, and the accurate location of the spot is then measured. These methods are often used in conjunction of stereo aerial photographs. The surveying team first measures several points that are clearly visible in the aerial photograph (often marked with a large plus sign in the terrain), and the stereo photograph is then straightened to correct and accurate coordinates. The stereo photograph is then used to measure enough points for the surface model [NK02].

In laser scanning, the accuracy of the points is somewhat compensated with amount of points. In this method an airplane flies over the ground and measures very large amount of points (using the distance and angle between the point and the plane and the GPS measured position of the plane). The problem with this approach is that it doesn't reliably distinguish between actual ground, a tree or a roof [JK01]. However, modern laser scanning software is capable of semi-automatically identifying objects, such as power lines, rivers and roads. It can also automatically reduce the amount of points with negligible loss or precision.

These methods are used to generate the model of the top-most ground layer. During the construction, soil, gravel, sand and rock behave quite differently, and hence the model often needs to represent the underlying rock surface as well. For this, the surveyors use drilling and ground radar techniques.

The output of the surveying phase is a set of 3D points – samples of the existing ground. The amount of points can vary between tens of thousands to several millions depending on the surveying method and the breadth of the design project. In some cases, representative break lines, such as ditches, ridges or sides of a road are measured. In that case, the input data will contain polylines in addition to separate points. In triangulation these are treated with chains of vertices between which there are known edges.

For existing structures, such as buildings and bridges, the old design model can often be used as the basis for the new design. In that case, some kind of adjustment measurement is usually done to ensure the location and the coordinates of the old model are in line with the new design.

3.2 Quality of the Input Data

The input data is never optimal. It always has some inaccuracy in it, and sometimes we even have no reliable error limit. If a sample point (x, y) has some error $(\Delta x, \Delta y)$ or if its measured height has some error Δz , this can be described as *geometrical inaccuracy*. However, the actual input data may have much worse logical errors. For example, two fold-lines might cross each other, or there might exist two points at same (x, y) —in the worst case with different Z . These are called *topological errors*. Sometimes, there are points whose height data is missing or wildly wrong. These can be denoted by *geometric errors*.

Apart from errors, there are several other quality criteria when surveying the ground. Obviously, the accuracy and amount of measurement points has a great importance. Because some surveying methods are cheaper and less accurate than others – e.g. stereo photograph surveying is cheaper and less accurate than that done with tachymeter – it is not simple to optimize the measurement for optimal costs. For that we need to approximate the cost of error. Jari Niskanen [Nis93] compares those two methods with 20 different data sets and finds that while photogrammetric measurements are generally much less precise, the results vary pretty much, and no rule of thumb can be given.

4 Triangulation Algorithms

4.1 Algorithms Categories

There are essentially six classes of algorithms for constructing a Delaunay triangulation from a point set:

- Sweepline algorithms that sweep the plane with a line and add edges to the triangulation as the line moves.
- Divide-and-conquer that recursively split the point set to a smaller subsets until the sets are trivial to triangulate and then merge the subsets.
- Greedy algorithms that start with one edge and incrementally construct the triangulation by adding one Delaunay triangle at a time.
- Refining algorithms that first form a non-Delaunay triangulation and then refine it with edge-flips until it satisfies the Delaunay criterion.
- Incremental algorithms that start with a trivial triangulation and incrementally add points to it while retaining the Delaunay property.
- Convex hull based algorithms that take advantage of the fact that the Delaunay triangulation of a point set in \mathbb{R}^2 is equivalent to the convex hull of the same points set projected onto a paraboloid in \mathbb{R}^3 .

(This use of term *greedy algorithm* was introduced by [DDMW94]. Some other sources use the term *greedy algorithm* for algorithms that start with a non-Delaunay triangulation and edge-flip it until it satisfies the Delaunay criterion. I use the term *refining algorithms* for that class of algorithms.)

Below, I present an example of an algorithm from each category.

4.1.1 Sweepline Algorithm

The sweepline algorithm was invented by Steven Fortune in 1986. It is often called the Fortune's algorithm [For87]. In the sweepline algorithm a *sweepline* and a *beach line* are maintained. Both of these lines are moved across the plane as the procedure advances. The sweepline is a straight line, and it moves from

top to down. At the any point of the process, the points above the sweepline have been processed and added to the triangulation, where as the points below it are yet to be processed. The beach line, on the other hand, is not a line, but a curve, consisting of parabolas. Above it, the Delaunay triangulation is known and fixed, and the points yet to be processed cannot affect it. There is one parabola for each point that has been processed, and it lies in the middle of the sweepline and the point so that at any point of the parabola, there is equal distance to the point and the sweepline. The beach line consists of the parabolas nearest to the sweepline and has an angle where the parabolas cross. Considering Delaunay triangulation, the concept of parabola curve beach line may appear awkward, but the correlation becomes clearer if we consider the dual of the Delaunay triangulation, the Voronoi diagram. Voronoi diagram divides the plane into regions whose any point is closest to the Voronoi point that defines the region. When the sweepline moves down, the beach line traces out the Voronoi diagram.

Fortune chose a binary tree to represent the beach line and its parabolas. He also maintains a priority queue of events that may in the future alter the beach line by introducing a parabola that crosses the ones in the priority list or removing a parabola from it. A parabola is removed when the sweepline becomes a tangent of the circle defined by three points whose parabolas form consecutive segments of the beach line. These events are prioritized by their y coordinate. As the sweepline moves, these events are added to the data structures, and the data structures are updated.

The sweepline algorithm has the run-time complexity of $O(n \log n)$ and memory use of $O(n)$ and in practice, it is one of the fastest algorithms after the divide-and-conquer algorithm. The algorithm is also well suited for producing Voronoi diagrams, because it produces them directly.

4.1.2 Divide-and-conquer Algorithm

This algorithm was first introduced by Lee and Schachter, but it was made popular by Guibas and Stolfi [GS85]. Guibas and Stolfi introduce a data structure they call a *quad-edge* that simplifies the implementation of the algorithm considerably. This data-structure maintains topological information about the triangulation and is useful in being able to satisfy queries about neighboring edge or face quickly. The core primitive in this data-structure is an *edge* structure. It has *origin* and *destination* vertices, and *left* and *right* faces as its member. In addition, it has methods to get the next *edge* from either origin vertex, destination vertex, left face or right face in counter-clockwise direction. The *vertex* structure holds the x , y and z coordinates of the vertex and a pointer to one adjacent *edge* such that the *vertex* in question is the origin *vertex* for the *edge*. For the other *edges* that have the *vertex* as the origin, one can iterate the *edge* structures, since they

always have a pointer to the next *edge*. Likewise, the *face* structure only has a pointer to each of its *edges*. The *edge*, *vertex* and *face* structures also have a unique id, so that they can be easily compared for identity.

The principle of the algorithm is simple: The points are first sorted by their x -coordinate. Then the points are divided into two halves, the halves are recursively triangulated and finally merged together. The recursion terminates when the size of the remaining point set is five or four. Four-point sets are divided into two two-vertex edges and five-point sets are divided into a triangle and a two-vertex edge. The two-vertex edges are treated as degenerated triangles and they are augmented into triangles in the later merge step.

The merge step is pretty complex. It is described as a bottom-up stitching process, in which some of the edges in the left triangulation and in the right triangulation are removed and new edge, so called cross-edges, are added. As the first step, we must find an edge that connects left and right triangulations and makes the bottom of the joint triangulation convex. After that, successive cross-edges are found in three-step process: (1) find the best vertex in left triangulation for a cross-edge connected to the origin of the topmost cross-edge, (2) find the best vertex in the right triangulation connected to the top-most cross-edge and (3) choose the best vertex from the two chosen in steps (1) and (2). This vertex is used as the destination of the new cross-edge. This stitching operation terminates when the topmost edge (the convex edge connecting the left and the right triangulation) has been added.

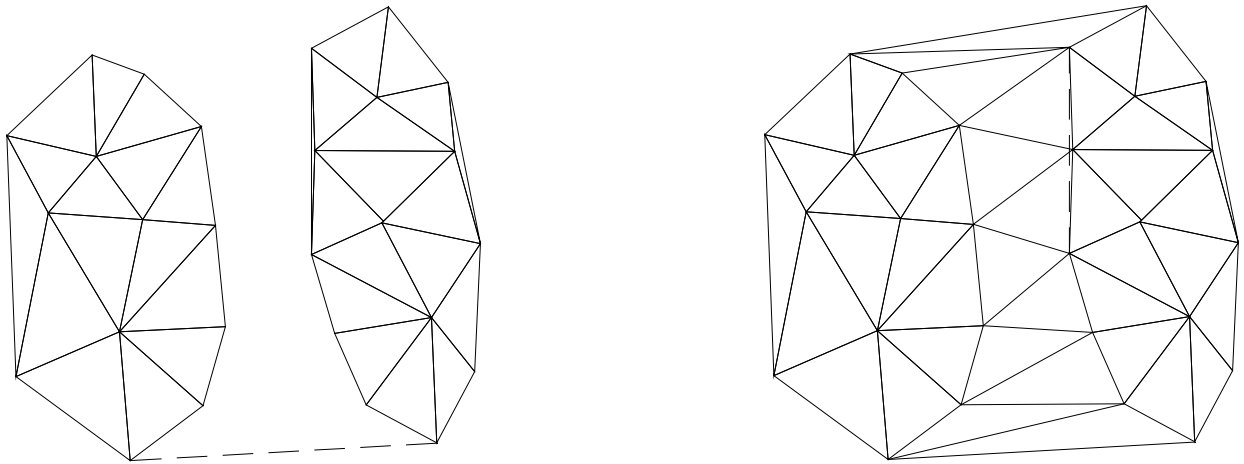


Figure 4.1: Divide-and-conquer Algorithm merge step. On the left, the new edge is denoted by dashed line. On the right, the removed edges are denoted by dashed lines.

The best vertex from the left triangulation is found by evaluating the vertices in the left triangulation that are connected by an edge to the top-most cross-edge. The vertices are evaluated in counter-clockwise order. Note that quad-edge data structure makes this iteration very easy. Initially, the first vertex is

assumed to be the best. The next vertex is better than it, if it is inside the circle defined by the current best vertex and the two vertices of the top-most cross-edge. If the next vertex is better, the temporary edge is deleted and a new one is added from the new candidate. This iteration stops when the candidate edge goes left (below) from the base edge. The candidate vertices from the right triangulation are found in symmetrical manner.

Intuitively, divide-and-conquer algorithm proceeds sub-optimally, since the recursion divides the point set into very long and narrow bands. Although these bands are triangulated so that they fulfil the Delaunay criterion locally, they are pretty far from the final triangulation that globally fulfils the Delaunay criterion. This short-coming in the algorithm has been noticed by many researchers and Rex Dwyer was the first to suggest an enhancement to in [Dwy86] by using altering vertical and horizontal splits.

4.1.3 Radial Sweep Algorithm

The radial sweep algorithm is a straight-forward refining algorithm that is easy to implement. It first finds a *center point* from the point set. The algorithm then counts the angles to all other points from the center point and sorts them by this angle and forms triangles between successive edges and in the non-convex notches. This initial triangulation is then refined with the iterative edge-flip procedure. Radial sweep algorithm was first described by Mirante and Weingarten in [MW82]. The initial triangulation produced by the algorithm is very poor: it contains almost solely long, thin triangles.

The algorithm proceeds as follows:

1. A *center point* is chosen from the point set. The center point is the one nearest to the middle of the point set.
2. Edges are formed between every point and the center point (Figure 4.2). These edges (and the corresponding points) are sorted by their angles (relative to the center point).
3. A triangle is formed between each consecutive edge (Figure 4.3).
4. The non-convex notches are then filled with triangles (Figure 4.4). This is done by iterating through the points (other than the center point). We denote the current point with P_c , the previous point in the sorted point list with P_p and the next point in the list with P_n . For each point P_c we count angle $\angle P_p P_c P_n$, and see if it is larger than 180° . This test tells whether P_c is an apex of a non-convex notch. A notch is made convex by adding edge $P_p P_n$ (and triangle P_p

$P_c P_n$). By applying this procedure for all points (but the center point), we get a convex, legal triangulation.

5. Step four forms an initial triangulation with many narrow triangles. The triangulation is now refined with the iterative edge-flip method in step (Figure 4.5) until it satisfies the Delaunay-criterion.

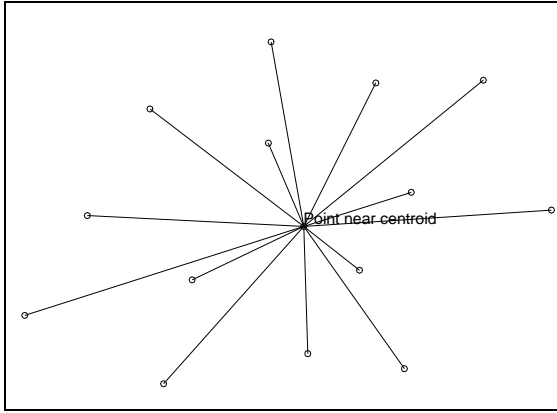


Figure 4.2: Initial edges sorted by their angles.

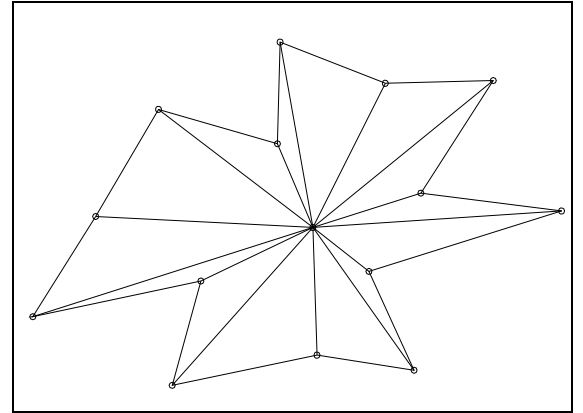


Figure 4.3: Triangles formed between the edges.

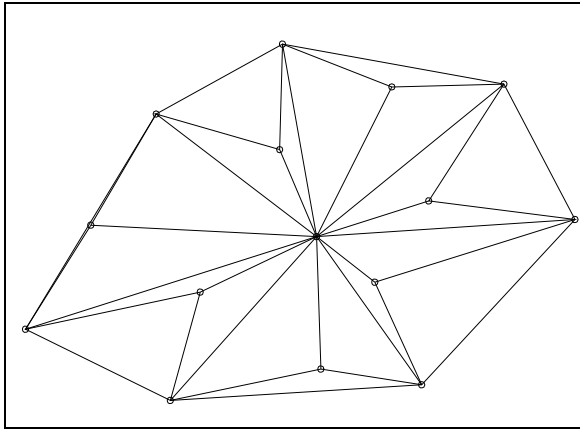


Figure 4.4: Non-convex notches filled.

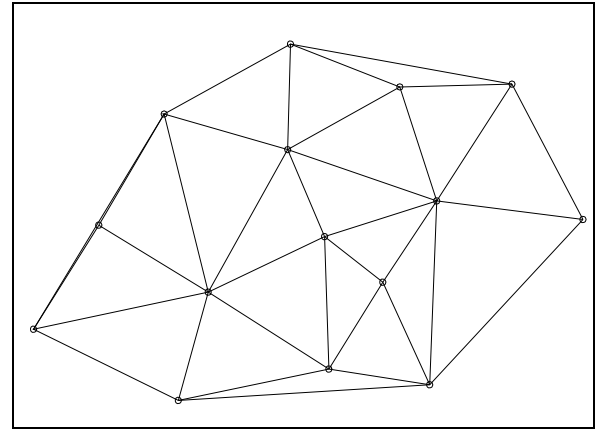


Figure 4.5: Triangulation is refined to satisfy Delaunay-criterion.

[MW82] uses a “shortest diagonal” criterion for the triangulation refinement: the diagonal of a triangle-pair is flipped if the new diagonal is shorter than the existing one. This flipping procedure is applied until no flips can be made. Shortest diagonal rule does not produce a Delaunay triangulation, and hence the

algorithm has later been modified to use maximum-minimum-angle rule, which yields a Delaunay triangulation.

The sorting step yields minimum complexity of $O(n \log n)$ for the radial sweep algorithm. This also applies to the worst case. The notch removal step has $O(n)$ complexity. The memory use of the algorithm is $O(n)$. The algorithm is not easily adaptable to higher dimensions.

4.1.4 Step-by-step Algorithm

Step-by-step construction algorithm is one of the most intuitive algorithms to construct a Delaunay triangulation. The basic operation in this algorithm is finding a suitable apex among the point set for a given edge, so that the apex and the edge define a triangle. The edge for which an apex is sought is called the (current) *base edge* [HD06].

When an apex that along with the base edge defines a Delaunay triangle is found, the triangle is added to the triangulation and the two new edges are inserted to the edges-to-process stack. A new base edge is taken from the top of the edges-to-process stack and the procedure is repeated.

The algorithm directly produces a Delaunay triangulation so no distinct refining step is needed. The distribution of points has big impact on the running time of the algorithm, and it could benefit from spatial coherence of the points with some adjustments to the apex searching phase.

The algorithm proceeds as follow:

1. Store all points into a search structure, such as quadtree.
2. Find the initial base edge. We need to find an edge that will be in the final triangulation. Since all the edges of the convex hull of the point set are members of the Delaunay triangulation, we can the shortest edge from the convex hull.
3. For the current base edge, find an apex candidate. This is done by enlarging the search circle gradually. The search circle always goes through the two vertices of the base edge and expands towards the center of the convex hull. If the base edge is part of an existing triangles, the search circle expands away from it. The search circle can be enlarged by for example doubling its radius every time. Using the quadtree, find points that are inside the search circle. If there is only one, select it. If there are several, select the one which forms the smallest circumcircle together with

the two base edge points. If the diameter of the circle is larger than maximum diameter of the convex hull and no points were found, mark the edge as orphan and go to step 5.

4. Add the triangle defined by the base edge and the apex point and its edges to triangulation. The two edges of the triangle that were not base edge are added into edges-to-process list unless they have two neighboring triangles.
5. Select a new base edge from the edges-to-process list. If there are none, the process has terminated and the triangulation is ready.

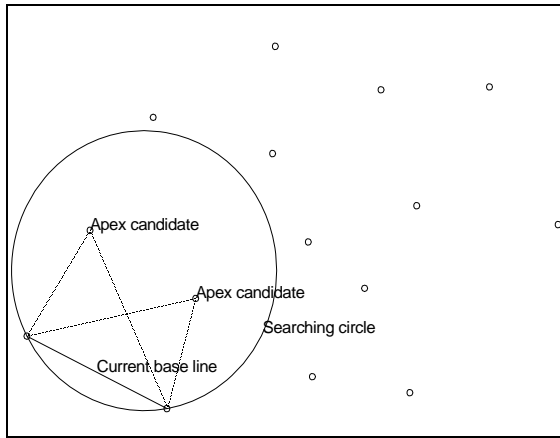


Figure 4.6: Initial base line is chosen and the first apex is sought.

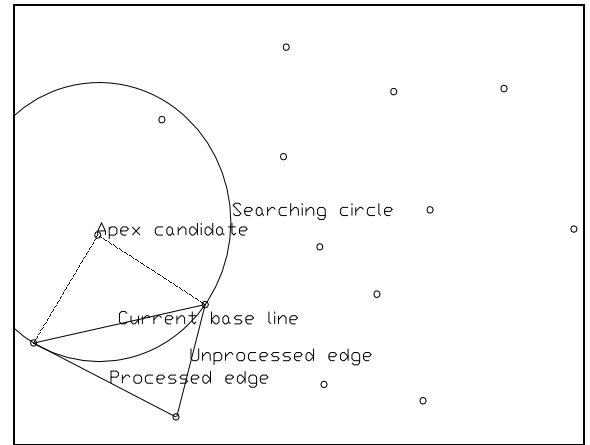


Figure 4.7: Two new edges are appended to edges-to-do stack and the topmost is used as base line.

4.1.5 Incremental Algorithm

The basis of the incremental algorithm is the point-insertion operation. The algorithm first forms a trivial initial triangulation (often a single triangle that includes the whole point set is used). Then all the points of the set are successively inserted to the triangulation using the point-insertion primitive (that maintains the Delaunay property). Finally, the artificial vertices that formed the initial triangulation are removed.

Guibas, Knuth and Sharir [GKS92] propose to randomize the points before adding them to triangulation to avoid any distortions that could increase running-time. Also, taking advantage of the spatial coherence of the points can decrease the running-time substantially (see section 4.1.7).

The algorithm proceeds as follows:

1. Form an initial triangulation that includes the whole point set. It can consist of a single triangle. This is done by taking the bounding box of the point set. Let a denote the width (in X -direction) and b the height (Y -direction) of the bounding box. Let X_{min} denote the smallest X -coordinate in the point set, X_{max} the largest X , Y_{min} the smallest Y and Y_{max} the largest Y . Then the vertices of the triangles can be chosen so that $P_1 = (Y_{min}, X_{min} - \frac{1}{2}b)$, $P_2 = (Y_{min}, X_{max} + \frac{1}{2}b)$ and $P_3 = (Y_{max} + a, X_{min} + \frac{1}{2}a)$. (In practice, it makes sense to choose the coordinates somewhat further from the point set, as it does not affect the result.) These artificial vertices will be removed from the triangulation later.
2. Each point of the point set is successively inserted to the triangulation while maintaining the Delaunay property. This is done with the following point-insertion procedure:
 - a. Insert the point (denoted by p) into the triangulation.
 - b. Locate the triangle t_e inside which point p lies. If point p lies on a boundary of a triangle, locate edge e_e on which point p lies. This is called the *search phase*.
 - c. If point p lies inside an existing triangle t_e , make three new triangles t_{n1} , t_{n2} and t_{n3} that have point p as the apex and each of the edges of triangle t_e as baselines. Remove t_e from the triangulation and add t_{n1} , t_{n2} and t_{n3} to the triangulation.
 - d. If point p lies on an existing edge e , denote the two existing triangles that share edge e_e , with t_{e1} and t_{e2} . Make four new triangles t_{n1} , t_{n2} , t_{n3} and t_{n4} that have point p as the apex and each of the four edges (other than e) of triangles t_{e1} and t_{e2} as their baselines. Remove t_{e1} and t_{e2} from the triangulation and add t_{n1} , t_{n2} , t_{n3} and t_{n4} to the triangulation. (If edge e_e is a boundary edge, only two new triangles are formed. The above description is trivially extended to cover this special case.)
 - e. If point p lies on an existing point, it is a duplicate and can be ignored.
 - f. The three or four existing edges that belong to the new triangles t_{n1} , t_{n2} , t_{n3} and (possibly) t_{n4} are called dirty. [BKOS97] shows that only the triangle-pairs whose middle-edge these dirty edges are will have to be checked for min-max criterion. Those of these triangle-pairs that do not satisfy the Delaunay criterion will be edge-flipped. This in turn may introduce new illegal edges. The check-edge-flip routine is thus called recursively until no edge is illegal. Note, that only two edges are potentially illegal after edge-flipping a triangle-pair: the two edges that belong to triangles not yet visited in this update cycle. This is enough to maintain the Delaunay property for the triangulation throughout the triangulation process. This is called the *update phase*.

3. After all the points in the point set are inserted into the triangulation, we have a Delaunay triangulation. The three artificial vertices inserted in step 1 are now removed along with the edges and triangles are connected to these vertices. The triangulation can now contain concavities, all of which can be dealt with by inserting triangles without affecting the existing triangulation. (Removing points and triangles from a Delaunay triangulation clearly cannot introduce situations where a point would lie inside a circumcircle of a triangle. Hence, removing the artificial vertices and the related triangles does not affect the topology of the Delaunay triangulation.)

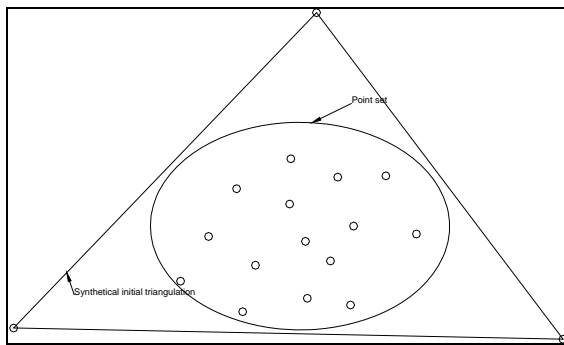


Figure 4.8: An initial triangulation is formed.

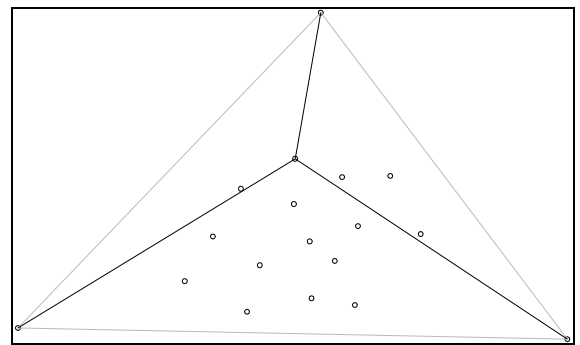


Figure 4.9: Points are inserted to the triangulation one by one.

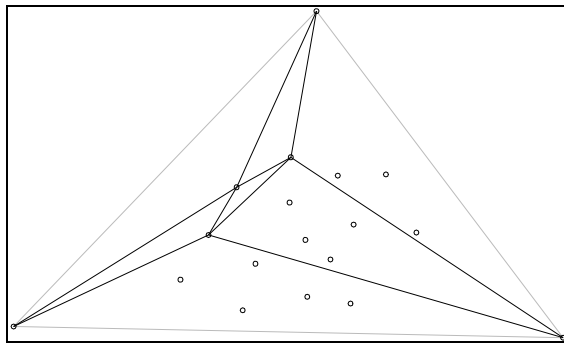


Figure 4.10: While inserting the points, the Delaunay criterion is maintained.

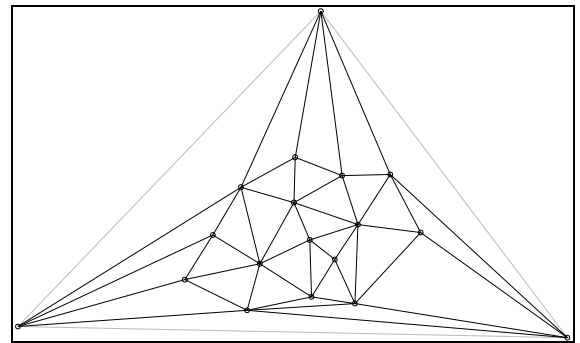


Figure 4.11: After inserting all the points, we have a Delaunay triangulation.

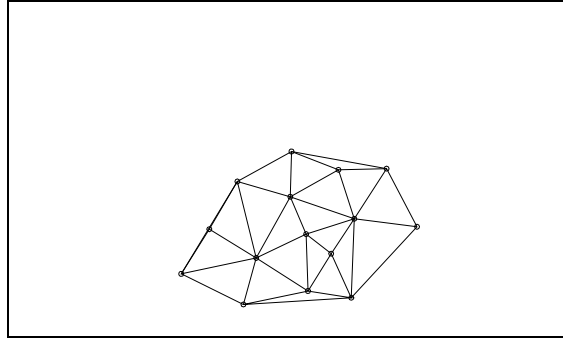


Figure 4.12: *The artificial vertices are removed and the triangulation is made convex again.*

Guibas and Stolfi show [GS85] that the worst-case performance of the update phase is $O(n^2)$, but that for uniformly distributed points, the expected running-time is constant giving total run-time of $\Theta(n \log n)$ for the algorithm.

4.1.6 Convex Hull Based Algorithms

As described earlier, the Delaunay triangulation of a point set in \mathfrak{R}^d is equivalent to the convex hull of the same points set projected onto a paraboloid in \mathfrak{R}^{d+1} . The edges of the lower convex hull, when projected back to \mathfrak{R}^d , form the Delaunay triangulation of the original points. Presenting a full algorithm for constructing convex hulls in higher dimensions is beyond the scope of this thesis, but I will present the rough idea. A well-known algorithm for convex hulls in \mathfrak{R}^2 is the quickhull algorithm presented by A. Bykat in 1978. This algorithm was generalized to higher dimensions by Barber, Dobkin and Huhdanpää in 1996 [BDH96]. The algorithm begins with a simplex of $d+1$ points. For each facet of the simplex, the algorithm considers the set of unassigned points, and assigns them to the outside set of the facet if they lie above the facet (above means outwards from the center of the simplex). Then for each facet with non-empty outside set, the algorithm selects the furthest outside set point and divides the facet into facets that go via the points of the original facet and via the farthest point. The new facets are considered again one by one assigning the points of the outside set of the original facet to the outside set of the new facets. The algorithm terminates when there are no points in the outside sets.

To generate the Delaunay triangulation of a point set in \mathcal{R}^2 , the points are first projected onto a 3D paraboloid

$$z = x^2 + y^2$$

In this case, the 3D convex hull consists of triangles. The triangles are projected back to \mathcal{R}^2 ignoring the ones whose normal doesn't point outwards from the paraboloid. The result is the Delaunay triangulation of the original point set.

4.1.7 Specialized Cases

In some cases it is worthwhile to take advantage of the known properties of the input data. Isenburg et al [ILSS06] describe a streaming algorithm to compute the Delaunay triangulation of a huge, well-distributed points set. The algorithm exploits the natural spatial coherence in a stream of points that is often present in real world data because of the way the surveying equipment operates. The algorithm is based on incremental algorithm described in section 4.1.5. The point data is first partitioned and tagged with finalization tags that indicate the point is the first in that region. The incremental algorithm can then take advantage of the partitions by removing the already processed areas from the active set and focusing on a small area at a time. They describe the speed up as stunning: they were able to process 11.2 GB of water radar point data in 48 minutes using only 70 MB of memory. This is only possible for data that has sufficient spatial coherency, but they claim that a large part of real world data has.

4.2 Point Data Triangulation with Fold-lines

The measured data usually does not consist of only points. Rather, obvious fold-lines, such as the base line of a drain, the side of a road or the wall-line of a building, can be included in the data. The fold-lines are polylines. They consist of points and edges that connect the points. The points of the fold-lines will appear as vertices in the final triangulation. The fold-lines define a fold that must appear in the geometry of the final triangulation. Therefore, no

triangle in the final triangulation can cross the fold-line, only touch it. It is easy to see that the edges of the fold-lines therefore also appear as edges in the final triangulation.

Due to this, I have chosen the approach of treating the fold-line edges as pre-defined and fixed edges in the triangulation process. This approach works well if the basic point-data triangulation algorithm is based on searching new triangles edge by edge. The only strictly needed modification to the algorithm is preventing the edge-swap function from touching “fixed” edges. The algorithm already has to find out whether the new edge candidates cross with existing edges (fixed or not), thus this introduces no problem.

Because fold-lines can introduce arbitrary constraints to the triangulation, the resulting triangulation rarely fulfils the Delaunay criterion. It is therefore difficult to unambiguously define the criteria for a fold-line-constrained triangulation. Obviously, fixed edges (fold-lines) are a mandatory criterion. But because fold-lines mandate only few edge-swap decisions, and all triangles cannot satisfy the Delaunay criterion, it is necessary to find a secondary criterion for triangle “goodness”. The min-max criterion used in the point-data triangulation turns out to be good for this. It has been proven that iteratively applying min-max –based edge-swap to an arbitrary TIN eventually yields a Delaunay TIN. Even if the TIN cannot satisfy the Delaunay criterion, applying min-max yields a good TIN that is as close to the Delaunay TIN as possible.

My algorithm obeys the following rules when deciding whether to perform an edge-swap for a triangle-pair:

1. If the triangle-pair’s middle-edge is fixed, do not swap
2. If the number of triangles that satisfy the Delaunay criterion is larger after the swap than before the swap, swap.
3. If the number of triangles that satisfy the Delaunay criterion is equal after and before the swap, use min-max criterion.

Since fold-lines are an additional constraint to the algorithm, they tend to increase running-time. It is, however, possible to try to exploit these constraints in some cases to avoid unnecessary searches on areas where no edge swaps can be made.

4.2.1 Other Approaches

Other approaches exist. The most commonly used approach is to triangulate the point-data (including the vertices from the fold-lines) like before. Then, a separate algorithm that takes the fold-lines and the point-data triangulation as input edge-swaps the triangle-pairs whose middle edge crosses the fold-line. (The triangulation in the neighborhood of the edge-swap can then be refined to be as close to Delaunay triangulation as possible).

The reason this approach is so popular is that it requires no changes whatsoever to the point data triangulation algorithm. It is possible to take a known-to-be-robust point data triangulation algorithm, and implement the fold-line support to it as a mere post-processing procedure. It does seem more optimal to take the fold-lines in consideration during the point data triangulation because

4.2.2 Additional Constraints

Often, additional fold-line related constraints are imposed to the triangulation. Most common of these is that a triangle in the final triangulation may not have two edges on the same fold-line. This is because the fold-lines are often altitude contours on an even altitude. If a triangle has two lines on a contour, it is obviously has the same Z for all points. This makes it impossible to unambiguously resolve the height line for that altitude from the resulting triangulation. Implementing this requirement to the triangulation algorithm is straightforward: rule out such triangles during the apex searching and edge-swap phase.

5 Manipulating and Using an Existing Triangulation

5.1 Adding a Point

To add a point to a Delaunay triangulation so that the resulting triangulation satisfies the Delaunay criterion, one can use the incremental algorithm steps 2 and 3 described in section 4.1.5. As discussed in section 4.1.5, it is enough to check the neighboring triangle-pairs for Delaunay criterion and possibly edge-flip them, and their neighbors recursively. While the worst case complexity of this is linear, the amortized complexity is constant for uniformly distributed points.

If the point lies on an existing triangle vertex, it can be ignored. If the point lies outside the boundary of the existing triangulation, a procedure somewhat dissimilar to the incremental algorithm point addition must be used. (Recall that in the incremental algorithm, it was first made sure that the initial triangle surrounds all the points to be triangulated.) In this case, searching clockwise-direction, we first find the first vertex on the boundary of the existing triangulation from which we can add an edge to the new point without crossing any existing edges. For this, it is enough to check the edges of the triangles connected to the candidate vertex. After this first vertex is found, we add an edge between it and the new point to the triangulation. We then continue iterating the vertices on the boundary clockwise adding edges to triangulation until adding an edge would cross an existing edge. We add a triangle between each successive new edge. After this, we must check each triangle-pair whose other triangle is a new triangle for Delaunay criterion and potentially edge-flip it. In this case, the complexity of point addition is $O(k)$, where k is the number of vertices on the boundary of the triangulation. For pathological cases, this can be as much as $O(n)$, where n is the number of points in the triangulation (if all the points are on a convex, arc like curve.) In practice, this is never the case.

In addition to the incremental method described above, there are other methods to update a Delaunay triangulation. Guibas and Russel [GR04] compare four different methods, and find that the incremental method is among the two fastest ones.

5.2 Adding a Set of Points

A set of points can be inserted with reasonable cost simply by iterating the procedure for adding a single point described in section 5.1. The amortized complexity of this is $O(k)$, where k is the number of points to be added.

However, certain special cases, optimizations can be made. If, for example, it is known that a large number of points lies outside the existing triangulation, and they are located so that a straight line can be drawn between them and the existing triangulation, the set of new points can be triangulated separately and then merged to the existing triangulation using the merge step of divide-and-conquer algorithm described in section 4.1.4. Unless the line is vertical, the merge step must be modified so that it evaluated its criteria relative to the line and not vertically. This is clearly non-trivial, and probably not worth the trouble in general case, but in special cases it could reduce the complexity of adding a set of points from $O(n \cdot k)$, where n is the number of triangles in the existing triangulation and k is the number of points to be added, to $O(k \log k + n)$.

5.3 Deleting a Point

Similarly to adding a point, removing one only affects the neighborhood of the removed point. We first remove the point, and the edges adjacent to it. We now have an empty polygon in the middle of the triangulation. (Unless the removed point was a vertex of a boundary triangle – if so, we leave the edge of that belonged to the boundary of the triangulation in place.) We triangulate this polygon and add the new triangles into the triangulation. Note that removing a point and its adjacent triangles from a Delaunay triangulation always yields a convex hole. Thus, the hole is very easy to triangulate.

The triangulation now doesn't fulfill the Delaunay criterion. We can now use the incremental algorithm update phase process described in section 4.1.5 with slight modifications: we call

the check-and-flip routine for all the new edges and the edges that are part of the boundary of the hole, and recursively for all the affected edges.

The worst case complexity of this is from $O(n)$, where n is the number of triangles in the existing triangulation, but amortized, it turns constant.

5.4 Deleting a Set of Points

If the points are scattered all over the triangulation, we can just call the single point removal routine outlined in section 5.3 repeatedly. The incremental algorithm update phase can be postponed to after all points have been added. This way, some edges do not need to be checked and swapped multiple times.

If we are to remove a large number of neighboring points (connected with one edge), we can first remove all of them and their adjacent triangles. This creates a potentially non-convex hole. This hole can again be triangulated as in section 5.3. Although triangulating non-convex is not as trivial as triangulating convex ones, there are many good algorithms for that. After the hole has been filled with new triangles, we update it to fulfill the Delaunay criterion as in section 5.3.

5.5 Folding with a Line or a Polyline

We often know certain vertices are connected by edges to form a ridge or ditch. This often the case for road plans or other built areas. Such ridge or ditch is called a fold-line because it folds the surface. A fold-line can consist of one or more line segments, i.e. it can be a polyline. Each line segment of the fold-line is a constrained edge in the triangulation: it cannot be edge-flipped even if it violates the Delaunay triangulation.

To add a new fold-line to an existing triangulation we must first make sure all its vertices are present in the triangulation. We add them into the triangulation with the incremental algorithm point adding method as described in section 5.2.

The next step is to make sure the new constrained edges are present in the triangulation. For each fold-line edge, we identify the triangles that lie between the vertices of the edge, remove them, add the new edge, and fill the hole to left and right of the new edge with triangles. We can apply the incremental algorithm update phase to the new edges (see section 4.1.5), but we cannot flip the new constrained edge. Hence, the triangulation will potentially not satisfy the Delaunay criterion anymore.

5.6 Simplifying the Triangulation

Simplification or *reduction* of the triangulation is a process where the complexity of the triangulation is reduced trying to maintain the properties of the triangulation as well as possible. The properties that need to be maintained depend on the application. If the triangulation is used for interpolation and volume calculation, the reduced triangulation must give as similar results as the original triangulation as possible. I.e. it must maintain the z coordinate at any given point as well as possible. If the triangulation is used for visualization, the reduced triangulation must look similar enough to the original triangulation from the given viewing distances and angles.

The purpose of the simplification is to save memory (both long-term and short-term) and processing time when using the triangulation. The triangulation might consist of millions of vertices, large majority of which are redundant for the given application.

There are different methods to simplify a triangulation. One can for example interpolate points on the triangulation at desired interval and then re-triangulate the new point set. This is usually too complex. A common approach is so called edge-collapse algorithm. In this algorithm, the edges of the triangulation are evaluated one at a time. For each edge, it is checked if it satisfies the collapse criterion (which can be fine-tuned, but usually takes the 2D length of the edge and the height difference of the edge in consideration and value them with certain weights.) If the edge is considered unimportant enough, it is collapsed: the triangles neighboring it are removed, and a new vertex is added in the middle of the removed edge. Each edge collapse reduces the triangulation with one point, two triangles and three edges.

Depending on the application, we may want to simplify the triangulation to certain amount of vertices (e.g. visualization with constant frame rate) or so that it still meets a quality criterion (interpolation). Straight-forward edge-collapse algorithm gives the latter, but it may be extended to give the former by iteratively applying the simplification several times relaxing the quality criteria each time until the triangulation has less than wanted amount of points.

One interesting development of triangulation simplification is a concept called *progressive meshes* [Hop96]. Much like progressive bitmap image formats (such as progressive JPEG), they can be used to transmit the mesh over network so that the receiving end can first present a rough shape of the mesh and it is then refined as the transmission proceeds. They can also be used to render large meshes with dynamic level of detail: higher detail near the camera and rougher representation further away. There are several methods to implement progressive meshes, but the initial idea by Hoppe was based on encoding the edge collapses and then applying them backwards when progressively enhancing the mesh.

5.7 Artificially Refining the Triangulation

A Delaunay triangulation that is contains the given input vertices (and edges) and nothing more may not be satisfactory to all purposes. While MWT is theoretically optimal, some argue that a Delaunay triangulation of a given point set is the optimal triangulation for interpolating heights. A Delaunay triangulation is good for many other purposes as well. It is worth noting, however, that if the input includes predefined edges, the resulting triangulation does not always fulfill the Delaunay criterion. The result might not be unambiguous either. Since there is only one possible Delaunay triangulation for a given point set (provided that it is in general position) it is not possible to enhance the triangulation without either breaking the Delaunay property or adding points. Breaking the Delaunay criterion is clearly not desirable. Altering a constrained triangulation (a contrivance we might get away without adding more non-Delaunay triangles) is not likely to give too good results either, since the triangulation is already produced using a metric to maximize its quality.

Despite being a Delaunay one, the triangulation at hand might still be unsatisfactory. It can contain long, narrow triangles (in particular, near its borders) that have very narrow angles. Another quality that is not always acceptable is the variance in the sizes of the triangles; the triangulation might contain very large and very small triangles. In many cases, homogeneity in this respect is desired.

What can we do to enhance the triangulation? One possibility is to intelligently add more vertices so that we can get rid of the narrow and large triangles. [Rup95] discusses one of the first good algorithms to do this. Ruppert's algorithm is guaranteed to yield a triangulation that satisfied the given bound for minimum angle while using relatively few triangles. Ruppert's algorithm proceeds in four stages. First, it produces a Delaunay triangulation of the input point set. At the second stage, it alters the triangulation so that it satisfies the fold-line constraints. The result of these two steps is a constrained Delaunay triangulation—producing such triangulation is discussed in depth in Chapters 5 and 6, so I'll omit the Ruppert's approach here. The third stage of the algorithm removes concavities and holes in the triangulation. This is because desired triangulation is not always convex; for example, a surface might contain a hole or a concavity where there is a lake or a spot where there is no measured data.

The fourth step of the Ruppert's algorithm is what is truly interesting. The algorithm adds vertices to the triangulation preserving the Delaunay criterion using a variant of the point addition algorithm discussed in 7.1. There are two cases in which the algorithm adds a vertex. First, if the diametrical circle of an edge (smallest circle that contains the edge) contains a point other than the two ends of the edge, a vertex is added in the middle of the edge. The two halves of the edge are then recursively checked for the same criterion and divided if necessary. Second, if a triangle has an angle that is smaller than the desired value, the triangle is divided by inserting a vertex in the center of its circumcircle. After the first condition (no other points on the circumcircle of an edge) has been dealt with, the second one will always add the vertex inside the triangle at hand because the triangle satisfies the Delaunay criterion. [Rup95] also discusses why this will always make the angles larger and proves that his algorithm halts for an angle constraint of up to 20.7° (with most inputs it terminates even with angle constraint of 33.8° .)

In 2.5-dimensional triangulations, the height of the added vertex is simply interpolated from the edge or from the triangle using the algorithm described in section 5.8. This ensures the area and volume of the triangulation doesn't change during the division.

Although Ruppert does not discuss it, the algorithm could easily be modified to also divide too large triangles simply by triggering triangle division for example with an area criterion: the 2D area of the triangle is calculated and the triangle is divided, if the area is smaller than the threshold.

5.8 Interpolating a Height Value for a 2D Point

In infrastructure design applications this is the most fundamental operation to be performed using a digital terrain model. Each time we add an object such as lamp post, traffic sign, or a corner of a building into the 3D construction plan, we must know where on the surface it lies. The x and y coordinates are given, but z must be interpolated from the digital terrain model.

For a triangulation, this operation is simple. First, locate the triangle the point lies in. If it lies on an edge, we can use either triangle. If it lies on a vertex, we can just return the height of that vertex, or use any of the triangles connected to that vertex to avoid special casing. Then, interpolate the height of the point from the triangle.

Interpolating a height of a point from a triangle is easy. Let us consider a vertex of the triangle to be the origin. Vectors v_2 and v_3 point from the origin vertex to the two other vertices and vector p points from the origin to the goal point. Let vector c to be the cross product of vectors v_2 and v_3 . The height of the goal point relative to the origin vertex then is

$$z = \frac{c_x p_x + c_y p_y}{-c_z}$$

For final result, we add the z of the origin vertex to that [HW99].

Unless we keep some kind of lookup index or have the triangles ordered somehow, locating the triangle has linear complexity, which is not acceptable. We can order the triangles by the

x coordinate or their leftmost vertex and record the width of the widest triangle (triangle whose leftmost vertex is furthest away from the rightmost vertex in x direction.) Then, we can use binary search to find the first triangle whose leftmost vertex is left of the interpolated point. We can then iterate triangles leftward until we find a triangle that contains the goal point. We can also terminate the iteration when we are further away (in x direction) from the goal point than the width of the widest triangle. If we haven't found the triangle that includes the goal point by then, it cannot exist in the triangulation. For an arbitrary triangulation, there is no guarantee that the widest triangle would not be very wide, perhaps as wide as the whole triangulation. This would turn this approach into $O(n)$ complexity. However, in Delaunay triangulation, the triangles are very well formed, so this cannot happen but for the most pathological cases.

If we choose to maintain the neighborhood information for each triangle in our final data structures (which triangle is neighbor of which triangle), we can enhance the algorithm somewhat. First we locate the initial triangle that is close to the goal point. We then draw a line from the center of that triangle to the goal point, and see which of the three edges of the triangle it intersects. We then move to the triangle that shares that edge with the current triangle. We then draw a new line from the center of the current triangle and repeat this process until we have found the triangle the goal point lies in (i.e. the line does not intersect any of the edge of the triangle.) This has the same worst case complexity, but is faster in practice. Maintaining the neighborhood information introduces a memory cost of 3 indices per triangle.

Although sorting the triangles by their x coordinate is free with regards to memory usage, it is suboptimal for searching the closest triangles. This is why many practical applications choose to maintain an auxiliary spatial index of the points. Most common type of index is the quadtree structure. A quadtree recursively subdivides an area into four segments: lower left, lower right, upper left and upper right [Knu98]. Each segment has its own sub-tree and is again divided in four sections until each segment contains less than certain amount of items. Such segment is a leaf of a tree and contains a list of elements that belong to it. For every segment (leaf or not), we know that the sub-tree pointed by it contains all the elements that lie on the area of the segment [BKOS97]. Although searching a quadtree takes logarithmic time, it is much faster than binary searching sorted triangles in practice.

5.9 Interpolating a Line or a Polyline

Another very common operation for digital terrain models in infrastructure design application is interpolating a line or a polyline onto the surface. Suppose for example that we are to build a house or a fence on the ground. We know the 2D polyline that defines the wall, but we also need to know where it lies on the ground.

For a triangulation, the procedure is as follows. For every line segment of the polyline, locate every triangle in the triangulation the line segment touches. Provided we have the neighborhood information available, we can use the neighboring triangle method described in section 5.8. First we find the origin triangle as when interpolating a point, using the start point of the line segment as the goal point. After this, we use the end point of the line segment as the goal point and use the line segment we have at all time, and do not draw a new line from the center of the current triangle. We also record the points where the line has intersected the edge of triangles. (The 2D location of those points will be the 2D intersection point of the edge and the line, and the z is the z of the edge at that point.) For the next line segment, we can omit the initial origin triangle search, since the end point of the previous line segment is the start point of the next. After interpolating the intersection points of a line segment, we interpolate the height of the start point of the line segment and prepend that point in the list of intersection points. If the line segment is the last, we also interpolate the last point and append that. The recorded point chain is now the interpolated polyline.

Unless we have the neighborhood information available, we need to search the triangles the line segment touches from a quadtree (or similar), and then intersect them with the line. Intersecting a triangle with a line in 2D gives two points if the triangle and the line intersect. For degenerated triangles, it can also give three, and if the line and the triangle touch at one point, it can give one. The former case can be ignored, because there should not be degenerate triangles in Delaunay triangulations. The latter case can be ignored, because it would not contribute any length to the polyline. It can also give three points, if the line comes into the triangle at a vertex and leaves through an edge. We can subvert this problem by defining the intersection so that a line does intersect an edge if it touches the start point,

but not end point. We form a line segment between these two points. Once we have intersected all the triangles the quadtree search gave us, we have a list of line segments that we will stitch together if they share a vertex.

5.10 Calculating Volume

In infrastructure construction, moving, removing and adding large quantities of soil material is a laborious and expensive operation. Suitable gravel must be brought in from a stone-pit far away, and even the waste soil can't be dumped wherever in urban environment. This is why the volumes of the soil materials must be known as accurately as possible. When the volumes are known, different design alternatives can be compared based on their cost.

There are two cases how volume is calculated from a digital terrain model. The simple case is when the volume is calculated against a given height (plane). The more complex case is when the volume is calculated between two surfaces.

Both of these cases are relatively straight-forward if we are only interested in the absolute volume between the two surfaces. However, in infrastructure design applications, we must often know how much of the surface is above (or under) the comparison plane (or surface) and give the 2D area, volume and bounding polylines of those areas. These are called the excavation and fill areas. We will come into that later.

The volume is usually calculated on a given 2D area, bounded by a given polyline. The first step is then to divide the surface with the bounding polyline. We first fold the triangulation with the boundary line as described in section 5.5. We then remove (or ignore) all the triangles outside the boundary line. If we are calculating the volume between two triangulations, we do this for the other triangulation, too. We now have two triangulations whose 2D area and projection are identical. We then calculate the volume between $z=0$ and the triangle (or z of the comparison plane). This volume is the 2D area of the triangle multiplied with the average of the heights of the vertices of the triangle (or height compared to the comparison plane). We take the sum of all these volumes to get the final absolute

volume. If we are comparing to a triangulation, and not to a plane, we calculate its absolute volume in similar manner and decrement it from the volume we calculated earlier.

If we must know the excavation and fill areas, we must first find the places where the surfaces (or surface and a plane) intersect. In case of plane, this is easy: first locate all the triangles in the triangulation that have (at least) one vertex below the plane and one above. Then calculate the line where the triangle intersects the plane. Then stitch a polyline out of these line segments. The polyline will either be closed or connected to the boundary polyline, in which case we can make it closed via the boundary line. We then fold the triangulation with these polylines and calculate the volume of each triangle. Positive volumes add to the fill volume and negative volumes add to the excavation volume.

For surface against surface calculation, we must fold both surfaces and calculate the volumes of the triangles of the both surfaces in similar manner. For each triangle we must see inside which fill or excavation boundary polyline it lies and add its volume to the fill volume or excavation volume accordingly.

6 Implementation Considerations

6.1 Robustness of the Triangulation Algorithm

As for example Guibas and Stolfi [Gui96] note, geometric data usually consists of both numerical coordinates (*numerical data*) and *combinatorial data*. For example, a polytope data structure contains a set of points whose coordinates are expressed with numbers (floating point, integer, rational) and whose connectivity is expressed with the order of the points. Obviously, the connectivity is unambiguous. But computing whether the polytope is convex is not. A small inaccuracy during the execution of the algorithm (such as rounding a floating point number) could disturb the algorithm if three points are nearly collinear. Even if exact arithmetic was used, the problem remains. Many intermediate results such as distances (which involve taking square root) cannot be expressed in rational numbers. Furthermore, even algorithms that can completely be calculated used rational numbers tend to suffer from

intolerable memory and CPU time requirements as the each calculation can add to the bit complexity of the rational numbers [For96].

Numerical precision, degenerate data sets or intermediate results, and other robustness issues continue to be the most challenging problem in implementing geometrical algorithms. Over the years, several strategies have been suggested to overcome the problems. Franco P. Preparata [Pre96] suggests dividing the operations in the algorithm in two categories: predicates and constructions. These operations have distinct role in the algorithm: predicates determine the branching flow of the program whereas constructions produce the output of the algorithm. The predicates need to be exact, but the constructions will require the precision that ultimately produces the output precision required by the application. The required numerical output precision can vary greatly – in raster graphics, for example, the requirement is pretty low – but if the predicates produce wrong results, the whole algorithm can produce (topologically) incorrect result.

Fortune [For92] studies the robustness of Delaunay triangulation algorithms. He uses approximate arithmetic, where operations $+$, $-$, \times and \div introduce error ϵ into the results and shows that some algorithms can be implemented so that the result is topologically correct even with such arithmetic. In particular, incremental algorithm (see section 4.1.5) can be implemented reliably in that case.

The IEEE 754 floating point numbers [VB04] are the de facto standard in modern computer programming. They are engineered to produce good results with limited precision (32 or 64 bit), while being very fast to implement in hardware. The IEEE 754 floating point numbers contain an exponent and mantissa parts as well as a sign bit. The exponent part expresses the magnitude of the number whereas the mantissa expresses the meaningful digits. This makes the location of the decimal point meaningless to the precision of the calculation. However, in the real world geometrical calculations, the locations are often expressed in global or country-wide coordinates, while the actual data site is relatively small. Because every location encodes both the global location and site-local position, several meaningful digits of precision are wasted. A common way to overcome this problem is to first find the center of the data set, then translate it near to the origin, calculate, and then translate the result back (if the result contains coordinates.)

An algorithm that calculates a triangulation takes both numerical and combinatorial input, but only gives combinatorial output. In addition, most Delaunay triangulation algorithms need to calculate distances; so using exact arithmetic is not a good solution. In reality it is not feasible to use anything but floating point numbers with data sets as large as hundreds of thousands of points. Even in future, when the available computing power and memory capacity will be larger, it is likely that the extra power will be used to tackle larger data sets. This, however, is ultimately a preference question, and the algorithm (if designed wisely) can be modified to use any kind of number representation.

With real world data sets, there is measuring error whose upper limit is not even always known. This will makes impossible to guarantee a robust triangulation—a small error in the data might cause the triangulation to be different from the right (Delaunay) one. What it is possible to guarantee, however, is that

- The triangulation is topologically correct:
 - edges do not cross each other
 - triangles are not inside each other (in 2D)
- the algorithm always produces the same triangulation given the same input (in whatever precision – the term “same” here means that the bit-representation of the coordinates is the same)
- the algorithm produces the same triangulation even if the point set is rotated on the XY plane (except when there are points whose distance from a Delaunay disc is smaller than the error that the rotation and related rounding can introduce)

6.2 Data Structures

Traditionally in infrastructure design software, the triangulations are presented as an array of points and array of triangles that contain three indices to the points array. For triangulating,

this data structure must usually be augmented with the neighboring triangles indices, three for each triangle, to represent the topology needed in the triangulation process.

Guibas and Stolfi [Gui96] propose the Quad-Edge data structure to implement the divide-and-conquer algorithm (see 5.1.2). In it, the edge is the central object, and it always contains links to the two neighboring triangles. See 5.1.2 for more detailed description of this data structure. It has the advantage that all the operations such as finding the neighboring edges and triangles are fast. It also consumes more memory than the triangle array data structure.

Shewchuk [She96] has implemented several Delaunay triangulation algorithms with both data structures. His findings are interesting. Despite the quad-edge based code being more simple and elegant, the triangle array (augmented with neighbor information) was generally as much as two times faster. Shewchuk made an innovative addition to the triangle array data structure: he added so-called ghost triangles where the triangles had no neighbors. These ghost triangles lack one vertex (a null pointer) and link to each other as neighbors in addition of the real boundary triangle. This got rid of several special case handling routines.

Like in so many algorithm design and implementation cases, the selection of – and even invention of – data structures plays crucial role here.

6.3 Multi-threading

With the multi-core processors becoming more and more common, parallel execution of heavy calculations is more and more important.

Most of the Delaunay triangulation algorithms are not easily parallelizable – because they modify the data structures at unlimited locations one would need to use very fine-grained locking to safely parallelize them. This would probably negate any performance gain available from parallel execution.

However, the divide-and-conquer algorithm (5.1.2) keeps the modifications localized. After each divide step, both point subsets can be triangulated in separate thread and then merged

together. The two threads can't add triangles into the same data structure, but to two separate data structures which are then merged into one much like in merge sort. The recursion can be modified so that a new thread is launched for each new point subset until desired number of threads (e.g. one thread per processor core) has been launched. After that, the algorithm can proceed normally.

In addition to divide-and-conquer algorithm, there has been research on parallelizing other algorithms. [KK03] describes how incremental algorithm can be made parallel. Jonathan C. Hardwick [Har97] describes an algorithm parallelizable over a cluster of workstations that uses an efficient subdivision method and fine-tuned serial algorithm for the recursion leaves.

6.4 Non-General Purpose Processors

In addition to multi-threading, a rising trend of computing in the few past years have been using non-general purpose processing units for general purpose work. An example of such processing units would be the graphics processing units found in the modern graphics adapters, and non-general purpose processing units like the IBM Cell processing units [Bar07]. Using the graphics processing units (GPUs) for general purpose work is called GPGPU. These units have tremendous processing power, but they can't be programmed with a general purpose programming language. Guodong Rong et al [RTCS08] have implemented algorithm to produce a Delaunay triangulation with GPGPU.

7 The Implementation and Evaluation

7.1 The Implementation

7.1.1 Data Structures

For my implementation, I chose a hybrid between the Guibas-Stolfi quad-edge structure (see section 4.1.2) and the triangle array data structures. This allows the triangulation algorithm to take advantage of the topological information that is the strong point of the quad-edge data structure, and at the same time, makes it easy to convert the existing triangle array based uses of triangulation to use the new data structures.

The Triangulation C++ structure contains an array of vertices, array of edges, an array of triangles and a quadtree of triangles. There is a quadtree of vertices, but it is only used for double checking that the none of the triangles contain other triangles (Delaunay criterion).

```
struct Triangulation
{
    Triangulation() : qtree(NULL) {}
    int AddEdge(int v1, int v2, int t1, int t2);
    int AddTriangle(int e1, int e2, int e3,
                   int v1, int v2, int v3);
    Array<Vertex> vertices;
    Array<Edge> edges;
    Array<Triangle> triangles;
    QuadTree<Triangle>* qtree;
    QuadTree<Vertex>* pointQtree;
    Point3d offset;

    BoundingBox GetBoundingBox();
    unsigned AddSurroundingTriangle(BoundingBox bbox);
    void RemoveSurroundingTriangles(int v1, int v2, int v3);
    void AddPointToTriangulation(int i);
    void SwapDiagonal(int edgeIdx, Hash<int, bool>& checked);
    void CheckEdge(int edgeIdx, Hash<int, bool>& checked);
    bool MinDiagonal(int edgeIdx);
    bool MinAngle(int edgeIdx);
    bool DelaunayCriterion(int triangleIdx);
    bool ConvexTrianglePair(int edgeIdx);
    bool FindOtherVertices(Edge& edge, int v[2]);
};
```

```
};
```

The Vertex structure contains three double precision floating point numbers: x, y and z via its base class Point3d.

```
struct Vertex
: public Point3d
{
    Vertex() {}
    Vertex(const double x, const double y,
           const double z = 0.0) : Point3d(x, y, z) {}
    Vertex(const Point3d& p) : Point3d(p) {}
    operator Point3d() { return Point3d(x, y, z); }
};
```

The Edge structure contains a link to the starting vertex, end vertex, and to the two neighboring triangles. It also contains its index in the edges array as a member so that two Edge structures can easily be compared for equality. Lastly, for lazy deletion, there is a valid flag, which when false tells the algorithm to ignore the edge.

```
struct Edge
{
    Edge() {}
    Edge(int v1, int v2, int t1 = -1, int t2 = -1)
        : v1(v1), v2(v2), t1(t1), t2(t2), valid(true) {}

    int v1;
    int v2;
    int t1;
    int t2;
    int idx;
    bool valid;

    int VertexIdx(int i);
    Vertex& V(int i, Triangulation& t);
    struct Vertex& V1(Triangulation& t) { return V(0, t); }
    struct Vertex& V2(Triangulation& t) { return V(1, t); }
    Line AsLine(Triangulation& t) { return Line(P1(t), P2(t)); }
    int& OtherNeighbour(int t);
    int& ThisNeighbour(int t);
    void Show(int color, Triangulation& t);
};
```

Based on the data members alone, not all topological information is directly available. The Edge structure implements helper method to get the index of the other neighboring Triangle based on the supplied index of the current triangle. Thus, the neighboring Triangles are available via the three Edges.

The Triangle structure contains a link to the three vertices, and to the three edges. It also contains an index to the triangles array and a valid flag. The Triangle implements a helper method to get the third vertex when given two others or an Edge. It also has a method to get the Edge when given two vertex indices.

```
struct Triangle
{
    Triangle() : valid(false), idx(-1) {}
    Triangle(int e1, int e2, int e3, int v1, int v2, int v3)
        : e1(e1), e2(e2), e3(e3), v1(v1), v2(v2), v3(v3),
          valid(true), idx(-1) {}

    int v1;
    int v2;
    int v3;
    int e1;
    int e2;
    int e3;
    int idx;
    bool valid;

    int VertexIdx(int i, Triangulation& t);
    Vertex& V(int i, Triangulation& t);
    int EdgeIdx(int i);
    int EdgeIdx(int vertexIdx1, int vertexIdx2, Triangulation& t);
    int ThirdVertex(int vertexIdx1, int vertexIdx2);
    int ThirdVertex(Edge& e);
    Edge& E(int i, Triangulation& t);
    Vertex& V1(Triangulation& t) { return V(0, t); }
    Vertex& V2(Triangulation& t) { return V(1, t); }
    Vertex& V3(Triangulation& t) { return V(2, t); }
    PointContainment IsInside(const Point3d &pnt,
                             Triangulation& s,
                             double* margin = NULL);
    BoundingBox& GetBoundingBox(void* ptr);
    bool TestBoundingBox2d(const BoundingBox& b, void* ptr);
    bool CheckValid(Triangulation &s);
    int Triangulate(int pidx, Triangulation &s,
                    int newEdge1 = -1, int newEdg2 = -1);
};
```

7.1.2 Triangulation Algorithm

The implemented algorithm is a variant of incremental algorithm (see section 4.1.5). Although incremental algorithm is not the fastest in many comparisons, it has expected running time of $\Theta(n \log n)$. Because the ability to insert a point or set of points into a Delaunay triangulation was needed anyway, I chose to implement the incremental algorithm.

The algorithm proceeds pretty much as described in 4.1.5. The auxiliary triangle is inserted first. Its vertices are selected so that the bounding rectangle of the point set is first enlarged by 10%. Then, the two lower points are added half width of the bounding rectangle away horizontally from the lower left and right corner of the rectangle. The upper vertex is added in the horizontally middle, and vertically one half width of the bounding rectangle below the top of the rectangle. These vertices are added to the end of the vertices array and their indices are memorized for later removal. A triangle and three edges are then created via these three vertices and added into the triangulation.

As a preliminary check, the point set is tested for duplicates and if there are any, they are removed. The point set (barring the three auxiliary points) is then shuffled into a random order to avoid any pathological behavior. Then the points are added, one by one, into the triangulation.

For each point, the triangle quadtree is consulted to find inside which triangle it lies. The quadtree search is rectangular, and may thus return unneeded triangles. Also, some of the triangles may be marked invalid. Because of this, the found triangles are checked in a loop and triangles that are either not valid or do not touch the point are discarded.

For each found and accepted triangle a *Triangulate* function is called. There should be one triangle if the point is inside the triangle, two if the point is on an edge, and several, if the point is on an edge. The last case should never happen, as there are no duplicates in the point set. If the point is inside, the *Triangulate* function divides the triangle into three new triangles, adding three new edges. The neighboring information is updated and the original triangle is marked invalid. If the point was on edge, the triangle is divided into two, and three new edges are added. The old triangle is marked invalid. *Triangulate* function is called

immediately for the triangle that shares the edges the point was on, passing the indices of the two new common edges as arguments. (If we would just let the loop visit the triangle normally, it would result in two new, duplicated edges. The loop will not touch the triangle again, since it is marked invalid. The new triangles are also added into the triangle quadtree.)

For each new edge created by the triangulation function, *CheckEdge* routine is called. It considers the two neighboring triangles of the edges, and checks if swapping the edge would result in smaller minimum angle among the six corners of the two triangles. If so, *SwapDiagonal* routine is called. *SwapDiagonal* routine changes the common edge to go between the two other vertices of the two triangles than the ones it originally goes. Neighboring information is updated, and the two updated triangles are removed and readded into the quadtree. For each four boundary edges of the triangle pair, *CheckEdge* is called recursively. As per the description in section 4.1.5, this recursion terminates when the neighborhood of new vertex satisfies the Delaunay criterion.

Once all vertices are inserted into the triangulation, the triangulation is a Delaunay triangulation, but includes the three auxiliary vertices. As the final step, all the triangles and edges connected to those three vertices and removed as are the three vertices. Then possible concavities are filled with triangles as the last step.

For validation purposes, the implementation also includes a *CheckDelaunay* function that goes through all the triangles and using the vertex quadtree checks, if there are any extra points inside the circumcircle of the triangle.

7.1.3 Complexity Analysis

The algorithm goes through all the points, which is $O(n)$. For each point, two non-constant time operations are executed: triangle quadtree lookup and recursive *CheckEdge* function call. The quadtree lookup is $O(\log n)$ for uniform data, and $O(n)$ very badly biased data, unless the quadtree is constructed specially or balanced on demand. As per section 4.1.5, the check edge recursion should terminate in $\Theta(\log n)$ normal data, but clearly it is $O(n)$ for biased data. Thus, the overall complexity is $O(n^2)$, should be $\Theta(n \log n)$ for non-biased data.

7.1.4 Interpolation Algorithms

The interpolation algorithm is very straight-forward. For point interpolation, the triangle quadtree is consulted to find the triangle the point lies in. If there are several, the first one will do. The triangle interpolation method described in section 5.8 is then used to get the height value.

For lines and polylines, the triangle quadtree is consulted to find the triangles that the line or polyline intersects in 2D. The interpolation is then done as described in section 5.9, and the result polyline is stitched together from the line segments.

Point interpolation is $O(\log n)$ for uniform data, and $O(n)$ very badly biased data. Polyline interpolation is $O(n)$ since a polyline can touch all the triangles in the triangulation. In practice, it is usually be $\Theta(m \log n)$ where m is number of vertices in the polyline.

7.1.5 Volume Calculation Algorithm

The implemented system can calculate the volume between two overlapping triangulations. It can give out the excavation and fill areas as colored areas and as volumes. The user may also supply a boundary polyline, inside which the calculation is to be done.

The boundaries of the two triangulations are calculated first. This is done by finding the edges whose other neighbor index is -1. A continuous polyline is then constructed out of these line segments. Next, the two triangulation boundary polylines and the optional user supplied one are merged together by taking the 2D intersection of them. The triangulations are then folded with this united boundary line.

After this, a three dimensional bounding box of the second triangulation is calculated. The triangle quadtree of the first triangulation is looked up for triangles inside this bounding box. Every found triangle is then considered one by one. For each triangle, the triangle quadtree

of the second triangulation is looked up for triangles that may collide with this triangle. For every potentially colliding triangle a triangle intersection function is executed and the potential intersection line segment is added to the array of collision lines. These line segments form the line where the two triangulations intersect.

Then, both triangulations are again folded with the intersection line segments. After this, we know that wherever the triangulations intersect, there is an edge and no triangle of either triangulation may lie partially above and partially below the other triangulation.

After this, we simple go through the triangles in both triangulations calculating the per triangle volume as described in section 5.10 and add the result into the volume total. For each triangle, we check if it is under the other triangulation, and add it into the excavation or fill area and volume respectively.

Because every triangle of either triangulation can potentially intersect several of the other, the calculation process is pretty heavy. The worst case complexity is in $O(m \cdot n)$ where n is the amount of triangles in the first triangulation and m is the amount of triangles in the second. In practice, the triangulations never collide at so many places, and the running time is tolerable even for large triangulations.

7.2 Environment

The implementation was developed and tested on as an Autocad run-time extension module (ARX), which closely resembles a DLL, on Windows Vista platform. The Autocad version used was Autocad Map 2008. Using Autocad allowed me to take advantage of the Autocad drawing and geometry functionality as well as easily import and export data sets. The source code was written in C++ and compiled with Microsoft Visual Studio 2005. The implementation depends on Vianova VidLib geometry library, which implements geometric primitives such as Point3d, Circle and Triangle (though Triangle was overridden in this project). The portability was not tested, but the implementation is plain C++, and should be portable to any other platform apart from the Autocad bindings that are separate from the calculation core.

The interpolation, volume calculation and surface intersection parts are part of Vianova Novapoint products, whereas the triangulation part itself was developed for this thesis and is not (yet) part of any product.

7.3 Evaluation of the Implementation against Other DTMs

7.3.1 Sample Data

To be able to evaluate the triangulation against a reference surface whose form is known absolutely, I chose a saddle surface

$$z = 15 \sin\left(\pi \frac{x}{20}\right) - 15 \sin\left(\pi \frac{y}{20}\right)$$

on area $x=[0, 100]$, $y=[0, 100]$.

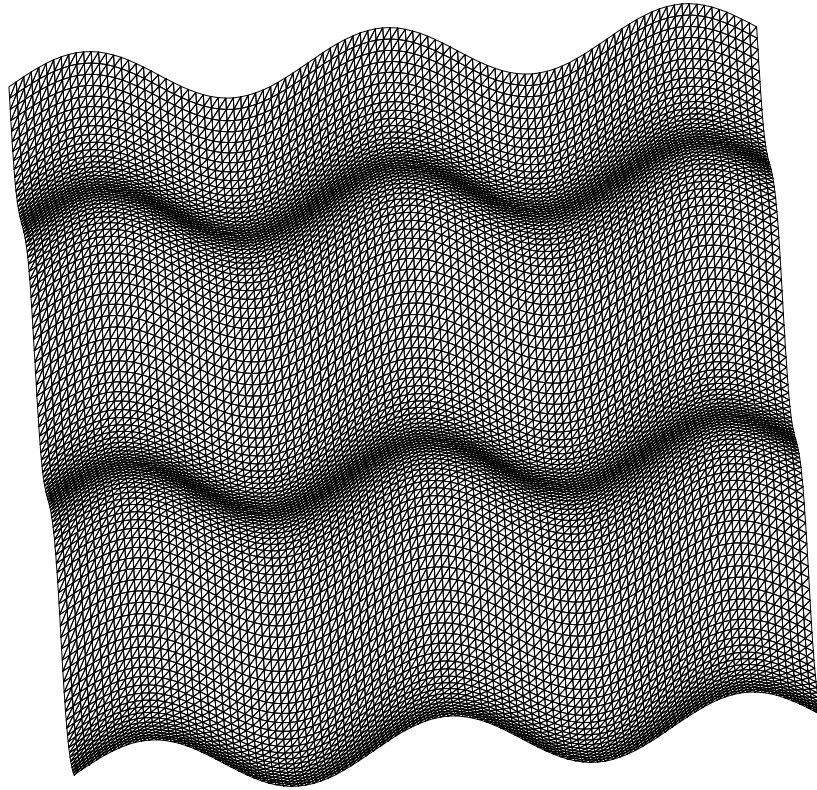


Figure 7.1: *The reference surface.*

Its intersection at $y=0$ or where y is a multiple of 20 is

$$z = 15 \sin\left(\pi \frac{x}{20}\right)$$

which makes is very easy to compare to the curves interpolated from the triangulation.

Its volume on area $x = [0, 100]$, $y = [0, 100]$ is 0, due to symmetry:

$$\begin{aligned} V &= \int_0^{100} \int_0^{100} 15 \left(\sin\left(\frac{\pi x}{20}\right) - \sin\left(\frac{\pi y}{20}\right) \right) dx dy = \\ &= \int_0^{100} \int_0^{100} \left[\frac{-300 \cos\left(\frac{\pi x}{20}\right)}{\pi} - 15x \sin\left(\frac{\pi y}{20}\right) \right] dy = \\ &= \int_0^{100} 300 \left(\frac{2}{\pi} - 5 \sin\left(\frac{\pi y}{20}\right) \right) dy = \int_0^{100} \left[300 \left(\frac{2y}{\pi} - \frac{100 \cos\left(\frac{\pi y}{20}\right)}{\pi} \right) \right] dy = 0 \end{aligned}$$

Also, the height of the surface is trivial to evaluate on any given 2D point.

The reference surface is hilly and should resemble a real ground surface. There are no steep slopes, acute folds, or local wrinkles so the surface is pretty obedient for the DTMs. However, it should provide a stable platform to compare different DTMs. Studying the different ground formations and how each DTM behaves with them would be interesting, but is not in the scope of this thesis.

For the actual sample data point set, I randomly sampled certain number of points. In addition, I add points one unit away from each other to the boundaries of the surfaces so that the convex hull of the point set is always square. These boundary points are counted in the number of points, so for $N=1000$, we have $101 + 99 + 101 + 99 = 400$ boundary points and 600 random points.

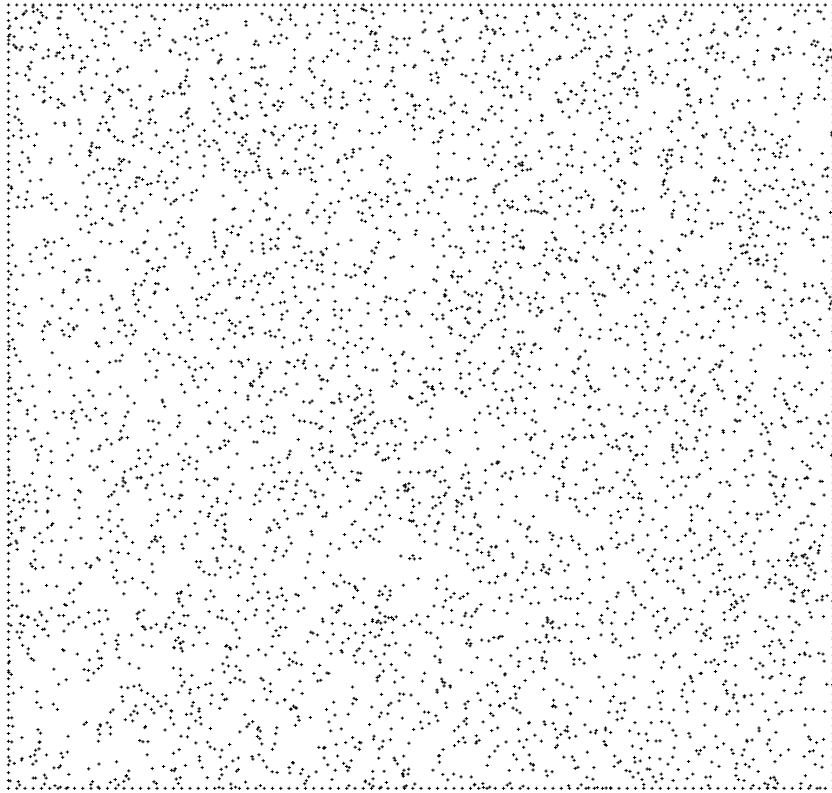


Figure 7.2: *Sample point set for $N=5000$.*

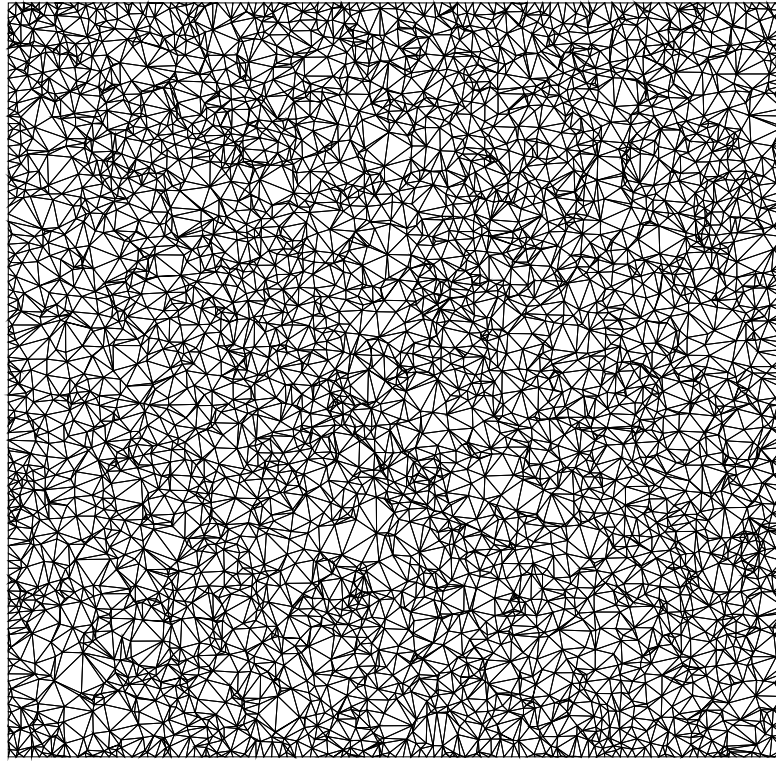


Figure 7.3: *The Delaunay triangulation of sample point set from Figure 7.2.*

I also measured the point interpolation height with a real world data set. The sample data set was a 45274 point set from Vuotos area shown in Figure 7.4. The triangulation run-time performance was measured with four real world data sets.

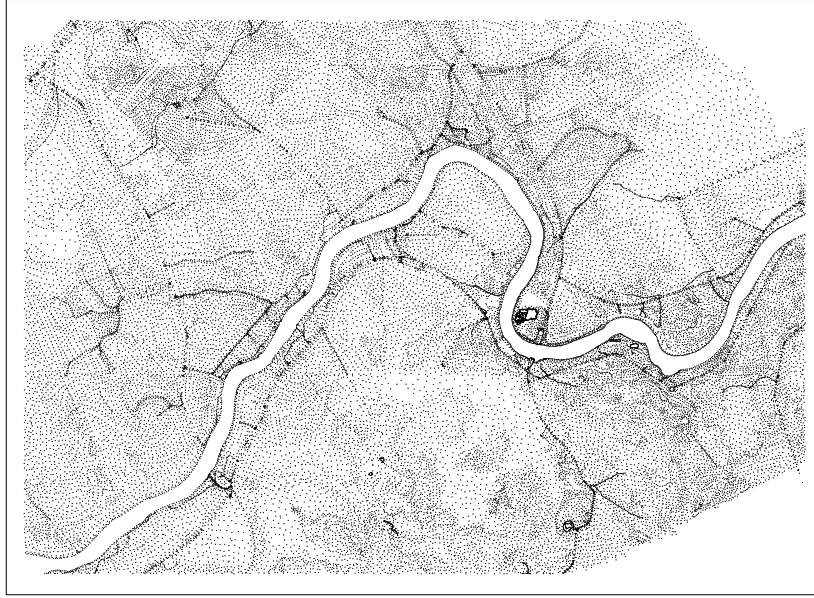


Figure 7.4: *The real world data set from Vuotos area.*

7.3.2 Other Digital Terrain Models

In addition to Delaunay triangulation, another popular digital terrain model in infrastructure design software is regular grid triangulation, also known as a square network. In regular grid triangulation, sample points are interpolated directly from the point set in regular intervals with normal point interpolation methods (see section. 2.3.1 and 2.3.4). Square or triangle network is then formed from these sample points.

To form the regular grid triangulation, I used interpolation function that takes N nearest points and takes the average height weighted by the inverse square distance from the goal point:

$$z_p = \frac{\sum_i z_{p_i} \cdot \frac{1}{\text{dist}(p, p_i)^2}}{\sum_i \frac{1}{\text{dist}(p, p_i)^2}}$$

In this work, $N=7$ was used.

From Figure 7.5 we can see that the artifacts described in section 2.3.4 show up in the triangulation.

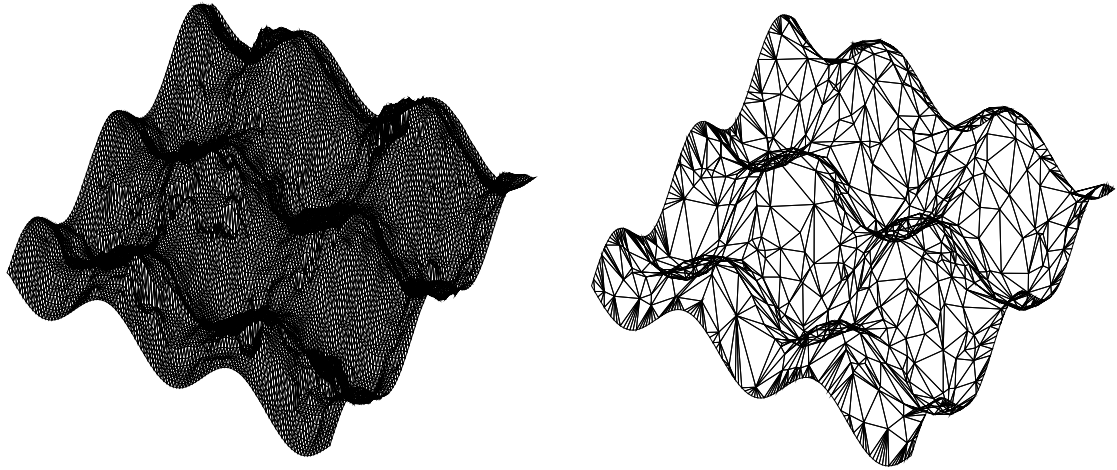


Figure 7.5: Comparing regular grid triangulation with side length of 1.0 for point set $N=1000$ to the Delaunay triangulation of the point set. We can see that the grid triangulation suffers from wrinkles.

In addition to Delaunay triangulation and regular grid triangulation, I compared direct point interpolation (see section 2.3.4), although it is not a surface representation and thus not applicable to volume calculation.

7.3.3 Run-time

The implementation has not been optimized and there are several identified places where it could be made faster by using more intelligent routines. However, its performance is not unworkable, and it is able to cope with half a million points, which is a relatively large data set in infrastructure design area.

The measurements were made on a Intel Xeon 5160 3.0GHz computer with 3GB of memory. The operating system was Microsoft Vista SP1 and the compiler Microsoft Visual C++ 2005 with optimizations turned on. The reported times are CPU time as reported by

the *GetProcessTimes()* function. The recorded run-times are the smallest out of 3 runs. The implementation runs on top of Autocad 2008.

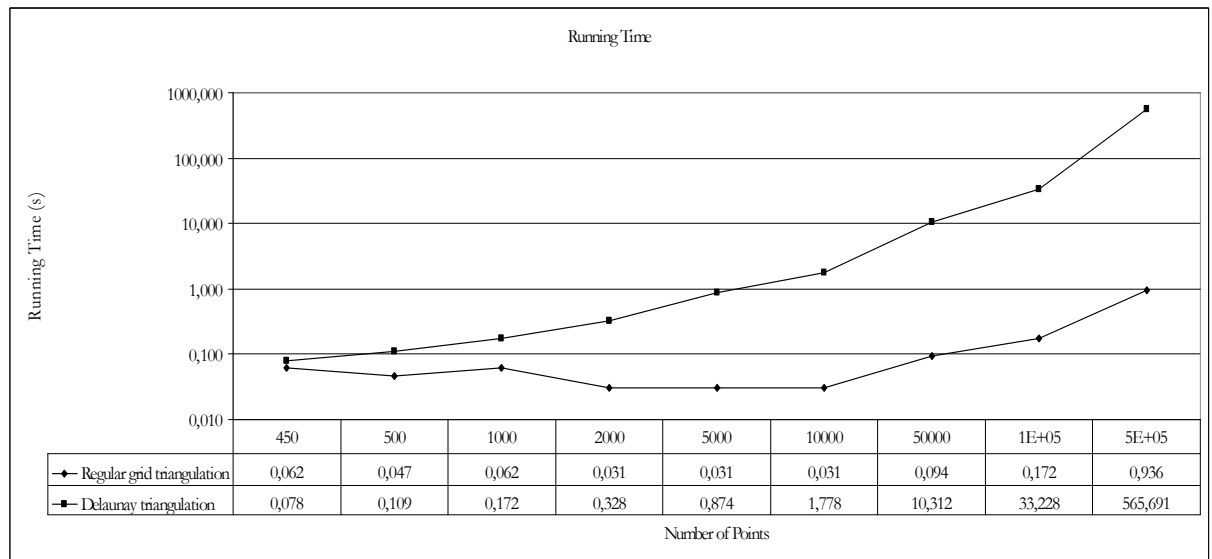


Diagram 7.1: The run-time of the two methods.

One interesting observation is that the regular grid triangulation actually gets slightly faster when number of points increases before it gets slower again. This is because with sparser point set, the point interpolation algorithm needs to look further and further away to find the 7 points. When the point set is dense enough that the 7 points are usually found on the first iteration, the algorithm begins to slow down again, as the quadtree gets deeper.

Jonathan Richard Shewchuk has compared [She96] four divide-and-conquer, two sweepline and two incremental algorithm implementations, all of which were highly optimized. He was able to get ten times better performance with alternating cuts divide-and-conquer algorithm than with incremental algorithm. Still, there is very much room for improvement in my incremental algorithm implementation, since Shewchuk's results were noticeably better for incremental algorithm than mine. Optimizing the implementation is not in the scope of this thesis.

I also compared the triangulation run-time with four large real world data sets: ground surface from Vuotos area (45274 points), a ground surface from Hamina VT7 design area (297835 points), a ground surface from Kaarina area (133163 points) and a ground surface

from Kirkkonummi – Kivenlahti KT51 design area (127828 points). The results were in line with the random data sets.

| Number of triangles | Number of points | Direct point interpolation CPU time | Regular grid point interpolation CPU time | Delaunay point interpolation CPU time | Regular grid volume CPU time | Delaunay volume CPU time |
|---------------------|------------------|-------------------------------------|-------------------------------------------|---------------------------------------|------------------------------|--------------------------|
| 622 | 512 | 0.484 | 3.182 | 8.003 | 0.047 | 0.047 |
| 3694 | 2048 | 0.562 | 3.931 | 6.318 | 0.296 | 0.312 |
| 15988 | 8192 | 0.718 | 3.354 | 7.504 | 1.248 | 1.310 |
| 65134 | 32768 | 0.671 | 3.245 | 9.407 | 5.195 | 5.179 |
| 261738 | 131072 | 0.796 | 4.867 | 22.745 | 20.483 | 35.241 |
| 1045458 | 524288 | 0.889 | 5.959 | 25.834 | 85.426 | 156.734 |

Table 7.1: The run-time of interpolation and volume calculation. The point interpolation times are for 100000 operations and the volume calculation times are for 10 operations. The times are in seconds.

The run-time of point interpolation was measured for 6 data sets, from 2^9 to 2^{19} points. The point sets were generated as before: first 400 boundary points and then $N-400$ random points. The point set was then triangulated giving slightly less than $2N$ triangles. For point interpolation, a set of 1000 random sample points was interpolated 1000 times – a total of 1 million operations. For volume calculation, the total volume was calculated 1000 times. For comparison, for each point set a regular grid triangulation was created with so that its side length gave about the same total number of triangles. (There was $N_t \pm 20$ triangles in the regular triangulation, where N_t is the count of triangles in the Delaunay triangulation. This was not meaningful difference for the measurements.) For point interpolation, direct point interpolation run-times were recorded as well. The recorded run-times are the smallest out of 3 runs.

In point interpolation, Delaunay triangulation was about 3 – 5 times slower than grid triangulation, and slightly slower in volume calculation, too. Considering the amount of operations, the differences are negligible, since in practice the interpolations are done with much less points at a time.

7.3.4 Accuracy in Interpolation of a Point

For testing point interpolation accuracy, I randomly sampled 1000 2D points from the area of the surface, calculated their exact height $z = 15(\sin(\pi x/20) + \cos(\pi y/20))$ and compared that to the height interpolated from the Delaunay triangulation and rectangular triangulation. Both average and maximum error are reported as a function of number of points in the triangulated point set.

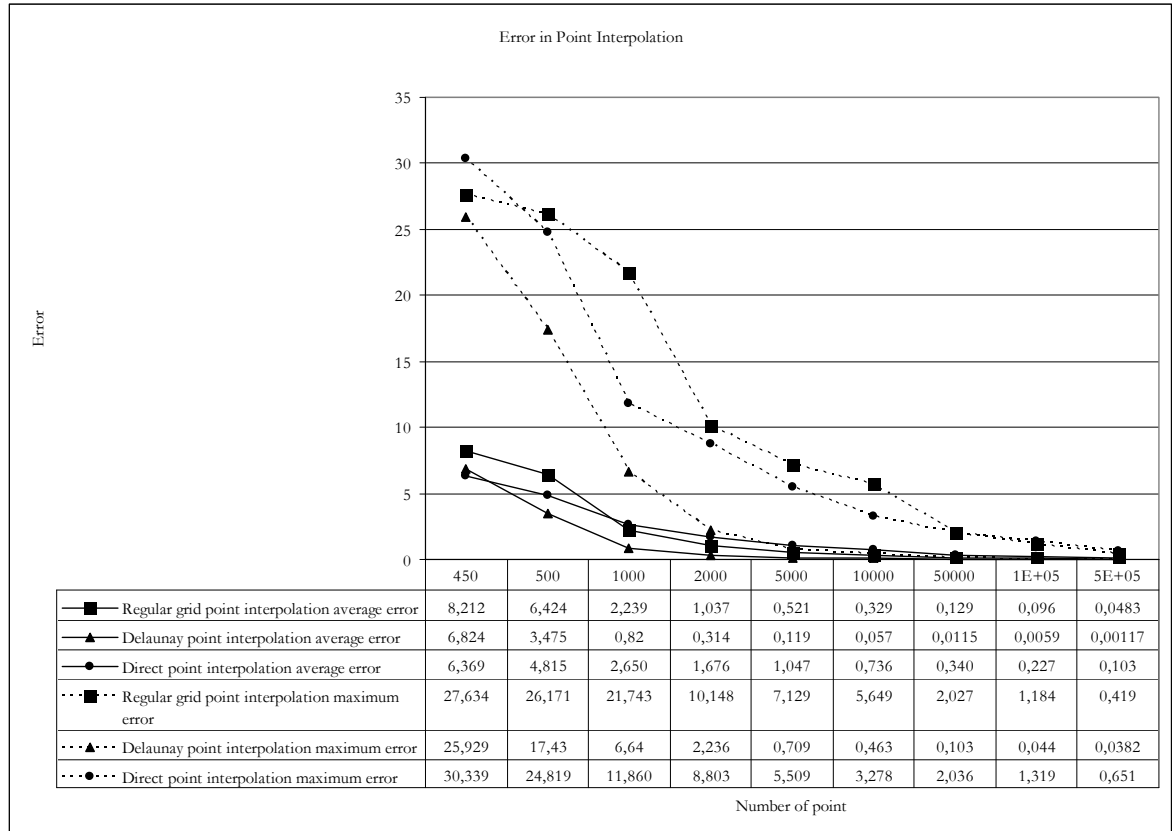


Diagram 7.2: The point interpolation error of the two methods.

From the results, one can see that Delaunay triangulation is able to reach acceptable accuracy with smaller N .

Its accuracy with $N=10000$ was 0.057 (0.19% of the total height range of 30), where as the regular grid triangulation had 0.529 (1.76%) and direct point interpolation 0.756 (2.52%). For

regular grid triangulation, the maximum error is very high even with $N=10000$ – 5.649 (18.8% of height range) – because regular grid triangulation suffers from unpredictable fluctuations. It is noteworthy that accuracy of 0.1 (10cm if we use meters as units) is not reached until $N=100000$.

The direct point interpolation function uses a slightly more elaborate way of deciding how many neighboring points it includes in the weighted average. The principle is the same as with regular grid triangulation point interpolation, but direct point interpolation considers max. 20 points if there are many near the goal point. Thus, it is able to achieve slightly better precision than regular grid triangulation with small N .

I also measured the accuracy of point interpolation with real world data. For that I took a ground surface surveying data set from Vuotos area (see Figure 7.4). The point set contained 45274 points, and their height varied from 157.34 to 183.67. The points had been measured by tachymeter and stereo photograph, and the point locations were selected by human. To approximate the accuracy, I created a Delaunay triangulation of the point set, and then selected 1000 points from the point set at random. I removed each point from the triangulation with the method described in section 5.3, interpolated the height, and inserted the point back. Because the height of the real surface was known (the height of the removed point), I could compare the accuracy of the triangulation without that point to the real height. For comparison, I did the same for direct point interpolation. The results are shown in Diagram 7.3. The Delaunay triangulation average error was 0.307 (1.17% of the whole height range), whereas direct point interpolation average error was 1.799 (6.83% of the whole height range).

Because the surveyed points are selected by humans, they usually selected so that they described the forms of the ground surface. Hence, just removing a point at random may not be optimal method to approximate the accuracy of the model – it may cause the DTM to miss some hill or valley of the real ground. However, there is no better way to measure the accuracy of real world data apart from re-measuring the sample points in the ground.

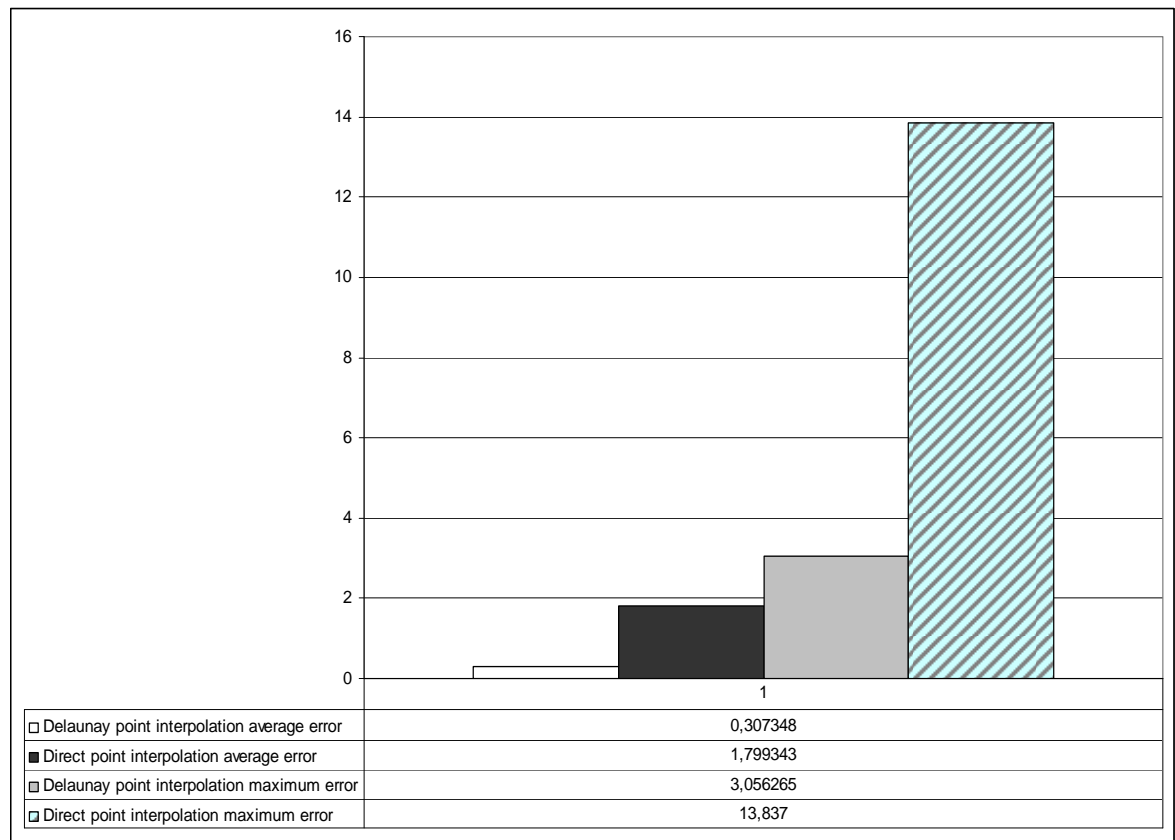


Diagram 7.3: Comparing the interpolation accuracy with real world data.

7.3.5 Accuracy in Interpolation of a Polyline

The algorithm to interpolate polylines is pretty much the same as for interpolating points. Hence, the error numbers are similar, too. The interpolated polyline profile can be telling, however. Below is the profile of a straight polyline at $y=10.5$ interpolated onto the surfaces. I chose a relatively low N of 1000 to underline the errors. From the profile we can see that with low N , Delaunay triangulation follows the reference surface much better.

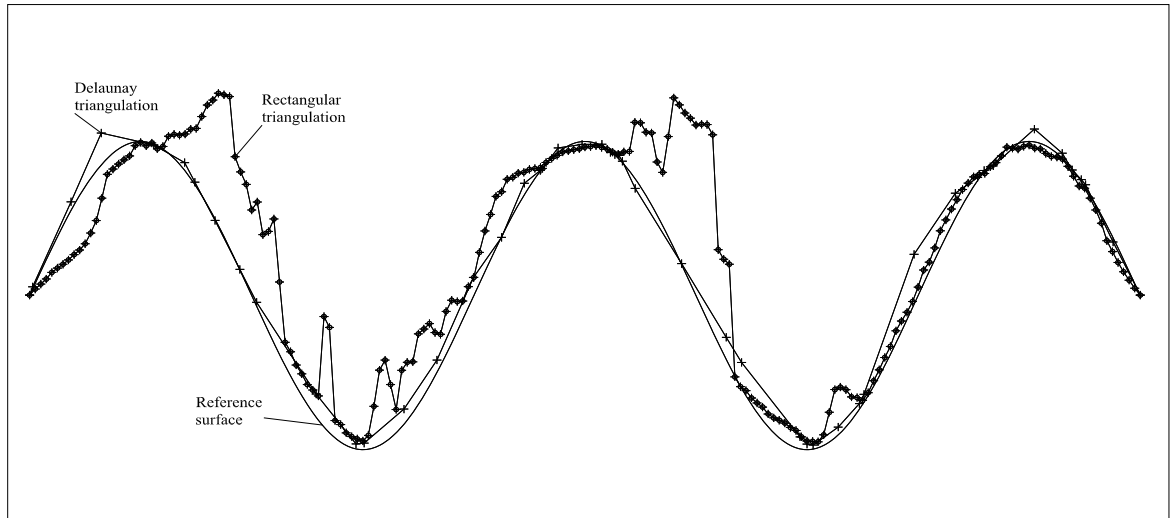


Figure 7.6: Comparing the intersections calculated from Delaunay triangulation and regular grid triangulation for $N=1000$.

7.3.6 Accuracy in Volume Calculation

To measure volume calculation precision, I calculated volume against plane $z=0$ with Delaunay triangulation and regular grid triangulation. The correct volume of the reference surface compared to plane $z=0$ is 0. From Figure 7.7, we can see how the hills above plane $z=0$ in the surface fill the valleys below the plane if the surface is rotated 90° .

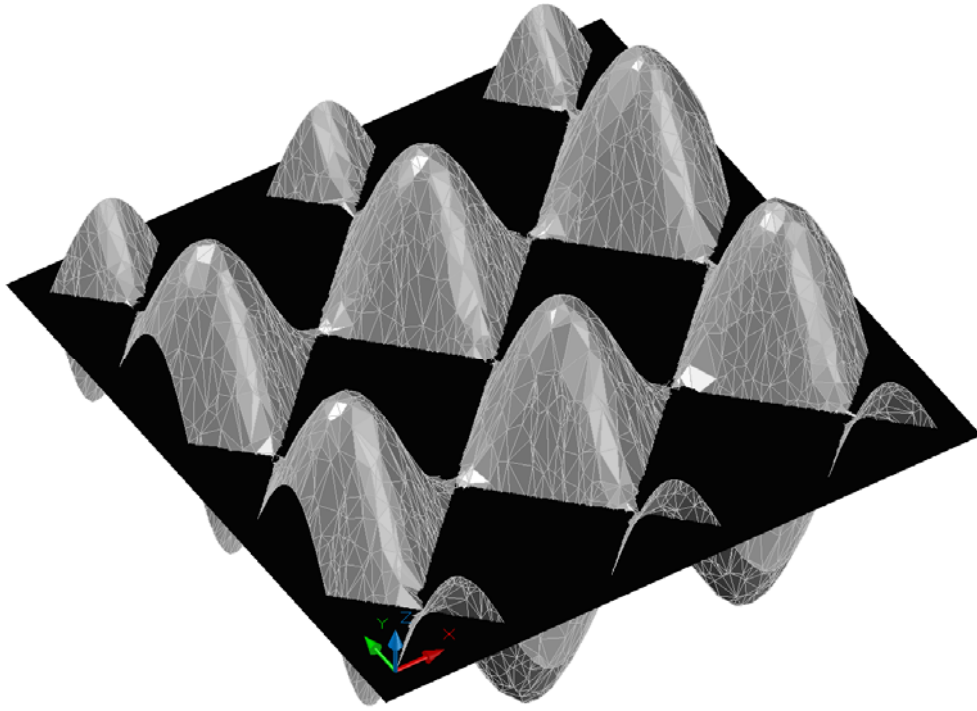


Figure 7.7: The sample Delaunay triangulation from Figure 7.3 compared to $z=0$. We can see that the hills are symmetric to the valleys if we rotate the surface by 90° and turn it upside down.

Although the volume calculation results fluctuate pretty much, the Delaunay triangulation reaches good precision much earlier, and regular grid triangulation has significant error even with $N=500000$ despite that much of the volume error cancels out since the triangulation can be both below and under the reference surface. Note that if we compare the volume errors to the area of the measurement (100000), the errors for $N=2000$ are not that high: 0.154 and 1.27 units per area unit for Delaunay triangulation and regular grid respectively. The total height range of the data set is 30 (from -15 to 15), so the volume of the enclosing cube is 300000. Compared to that, the errors for both method are under 0.06% at $N=2000$.

| N | N disregarding boundary points | Regular grid triangulation volume | Delaunay triangulation volume |
|--------|-----------------------------------------|-----------------------------------------|-------------------------------------|
| 450 | 50 | -7538.522 | -16021.772 |
| 500 | 100 | 11334.505 | 1183.620 |
| 1000 | 600 | -2969.992 | -447.397 |
| 2000 | 1600 | -154.249 | -127.825 |
| 5000 | 4600 | -13.358 | -3.068 |
| 10000 | 9600 | 19.272 | 11.152 |
| 50000 | 49600 | 24.705 | -0.378 |
| 100000 | 99600 | 15.941 | -0.151 |
| 500000 | 499600 | 3.915 | -0.000886 |

Table 7.2: The volume calculation results of the two methods.

I also compared the volume calculation precision when calculating the Volume between two surfaces. For the first surface I used the same surface as in the previous measurement. For the second surface, I chose

$$z = 15 \sin\left(\frac{\pi x}{20}\right) - 15 \sin\left(\frac{\pi y}{20}\right) + 5(x - 50)$$

on area $x=[0, 100]$, $y=[0, 100]$. Its volume on area $x=[0, 100]$, $y=[0, 100]$:

$$V = \int_0^{100} \int_0^{100} 15 \sin\left(\frac{\pi x}{20}\right) - 15 \sin\left(\frac{\pi y}{20}\right) + 5(x - 50) dx dy$$

is also 0. Hence, the volume difference of the two surface on area $x=[0, 100]$, $y=[0, 100]$ is 0.

For comparison, I calculated the volume differences with the square grid method described in section 2.3.1 and Figure 2.9. For square grid method I used square count roughly equivalent to triangle count in the corresponding Delaunay triangulation. The sample point sets were the same random point sets for both methods.

| Number of points | Number of triangles | Number of squares | Delaynay triangulation volume difference | Square grid volume difference |
|------------------|---------------------|-------------------|------------------------------------------|-------------------------------|
| 1000 | 1598 | 1600 | 352.974 | 12653.775 |
| 2000 | 3598 | 3600 | -93.084 | -12271.448 |
| 5000 | 9598 | 9604 | -12.280 | -8425.669 |
| 10000 | 19598 | 19600 | 5.849 | 10093.615 |
| 50000 | 99596 | 99225 | -0.892 | -12881.373 |
| 100000 | 199600 | 198916 | 0.281 | -9321.218 |
| 500000 | | 1000000 | | -1211.029 |
| 1000000 | | 2000000 | | -8848.756 |

Table 7.3: The volume difference calculation results of the two methods.

The volume difference of Delaunay triangulation stabilizes pretty soon, but the square grid results fluctuates badly. The square grid results are equivalent of average interpolation error of ~ 1 over the whole area. The error is unexpectedly high, but the result was verified several times. It is possible that the second surface is pathological for the square grid method.

7.3.7 Previous Work

Niskanen [Nis93] measured the effect of removing points and fold-lines from input data. He used the square grid volume calculation method, but interpolated the heights from triangulations. He doesn't mention if the triangulations were Delaunay ones, but at least with fold-lines the triangulations were unlikely to fulfill the Delaunay criterion. Niskanen found that among his 8 different data sets, the results varied greatly. The best data set was able to withstand (randomly) reducing the point count to one fourth without a great loss precision, but the worst data set exhibited bigger precision loss with reduction to $2/3$ than the best with reduction to $1/4$. Niskanen suggested that the effect of the human selected fold-lines in the input data is crucial here.

Bonin and Rousseaux [BR05] describe algorithms to predict which areas in height-line based DTMs belong to categories "likely over-estimated", "likely underestimated", and "with no significant bias". Their algorithm produces a qualitative description of local uncertainty, which they claim is more relevant for geographical applications than global quality parameters.

8 Conclusion

The main concerns in modeling surface in infrastructure design software arise from the high accuracy and correctness needs of the application domain. Errors in the calculations may not only cause large costs and delays, but also expose the built structure to the risk of collapsing. On the other hand, the surveying the surface to get high number of accurate sample points is costly and slow. Therefore, it is crucial that the digital terrain model constructed from the sample points is as good as possible. Traditionally, the infrastructure design software packages have used simple grid base surface approximations because they are easy to implement and they have low run-time cost.

This Master's Thesis has described various digital terrain models and how Delaunay triangulation compares to them. I have discussed various theoretical properties of the Delaunay triangulation and how they are desirable for infrastructure design applications. I have outlined several ways to construct a Delaunay triangulation, and described one Delaunay triangulation algorithm implementation in detail and the challenges in implementing it. I have also described how Delaunay triangulation can be used to point and polyline interpolation and to volume calculation, which are the most important infrastructure design application operations for DTMs.

I have measured the running-time of the implementation and compared it to two other DTM variants in both constructing the DTM and using it for interpolation and volume calculations. I have measured the accuracy of the DTM variants with ideal and real world data sets in interpolation and volume calculation.

The measurements show that the accuracy of Delaunay triangulation in infrastructure design application – in particular, point interpolation and volume calculation – is good, and it doesn't suffer from unpredictable spikes. The Delaunay triangulation achieves good accuracy with considerable smaller amount of input data, which translates into smaller costs in surveying the ground surface. With modern hardware, its run-time performance is

comparable to other methods, and in practice, it is not the bottle-neck of the design process. The small performance penalty is easily won back in shorter surveying time.

A part of infrastructure design software available commercially today still uses DTMs other than Delaunay triangulation for interpolation and volume calculation. Based on this research, this can only be because they are easier to implement than Delaunay triangulation, not because they would have other desirable properties. Based on my experience, the Delaunay triangulation algorithms – while simple on paper – are pretty complex and laborous to implement in practice. They are also more prone to implementation bugs than the simpler DTMs. These problems are not insurmountable, and the work invested in perfecting the Delaunay triangulation implementations should not be high compared to the advantages.

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